Wireless Mesh Networks

Alvin Albuero De Luna

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LIST OF ABBREVIATIONS

AC	Access Category
ACKs	Acknowledgments
ACs	Access Categories
AIMD	Additive Increase Multiplicative Decrease
AODV	Ad Hoc On-Demand Distance Vector
ATP	Ad Hoc Transport Protocol
BDP	Bandwidth-Delay Product
BER	Bit Error Rate
BLC	Bottleneck Link Capacity
CA	Collision Avoidance
CAP	Contention Access Period
CCA	Clear Channel Assessment
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CDMA/CA	Carrier-Sense Multi-Access with Collision Avoidance
CFP	Contention-Free Period
CIR	Carrier-to-Interference Ratio
CSC	Channel Switching Cost
CSI	Channel State Information
DCCP	Datagram Congestion Control Protocol
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DSL	Digital Subscriber Line
DSR	Dynamic Source Routing
EBL	Electronic Brake Lights
EBT	Expected Busy Time
EDCA	Enhanced Distributed Channel Access
EDR	Expected Data Rate

ELFN	Explicit Link Failure Notification
ENT	Effective Number of Transmissions
ETOP	Expected Transmission on a Path
ETX	Expected Transmission Count
FDD	Frequency Division Duplex
FFD	Full Function Device
GPSR	Greedy Perimeter Stateless Routing
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HT	High Throughput
IRU	Interference-Aware Resource
ISPs	Internet via Service Providers
ITS	Intelligent Transport Systems
LANs	Local Area Networks
LCMR	Light Client Management Routing
LOS	Line-of-Sight
LQCA	Link Quality and Congestion Aware
MAC	Medium Access Control
MAI	Multiple Access Interference
MAN	Metropolitan Area Networks
MANETs	Mobile Ad Hoc Networks
MEMS	Microelectromechanical System
MIB	Management Information Base
MIC	Metric of Interference
MIMO	Multiple Input Multiple Outputs
MMAC	Multichannel MAC
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
NAV	Network Allotment Vector
NAVC	Network Allotment Vector Count
NLOS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
ORR	Orthogonal Rendezvous Routing
PAN	Personal Area Network

PCA	Prioritized Contention Access
PER	Packet Error Rate
PHY	Physical Layer
PLCP	Physical Layer Convergence Procedure
PLME	Physical Layer Management Entity
PLR	Packet Loss Rate
PMD	Physical Medium Dependent
PPD	Packet Pair Delay
PPDU	PLCP Protocol Data Unit
PSD	Power Spectrum Density
PSDU	Packet Service Data Unit
RCP	Rate-Control Protocol
RFD	Reduced Function Device
RIFS	Reduced Interframe Space
RIP	Routing Information Protocol
RMS	Root Mean Square
RSVP	Resource-Reservation Protocol
RTS/CTS	Demand to Send/Clear to Send
RTSP	Real-Time Streaming Protocol
RTT	Round Trip Time
SAP	Service Access Point
SCTP	Stream Control Transmission Protocol
SIFS	Short Interframe Space
SINR	Signal-to-Interference-Noise Ratio
SNR	Signal-To-Noise Ratio
SSCH	Slotted Seeded Channel Hopping
STC	Space-Time Coding
SVD	Singular Value Decomposition
TBRPF	Topology Broadcast Based on Reverse-Path Forwarding
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TEDS	Transducer Electronic Data Sheets
TSF	Time Synchronization Function
UDP	User Datagram Protocol

UWB	Ultra-Wideband
VANETs	Vehicular Ad Hoc Networks
WCETT	Weighted Cumulative Expected Transmission Time
WEP	Wired Equivalent Privacy
WLANs	Wireless Local Area Networks
WMNs	Wireless Mesh Networks
WPANs	Wireless Personal Area Networks
WSNs	Wireless Sensor Networks

PREFACE

Wireless mesh networks (WMNs) will dominate in the coming decade as they are one of the primary technologies. They will assist in understanding the awaited dream of network connectivity anywhere, at any time, at a low cost. As a result, in the next-generation Internet, they will play a significant part. Their ability to self-organize greatly minimizes the complexity of network implementation and maintenance, necessitating a low initial investment.

Simple mesh clients and mesh routers make up these networks, which make the backbone of WMNs. Mesh routers have limited mobility. They connect mesh and traditional clients to the network. The bridge functionalities and the gateway in mesh routers can be used to connect WMNs to other networks like the cellular, Internet, IEEE 802.16, IEEE 802.15, IEEE 802.11, sensor networks, etc. Mesh clients can be mobile or motionless, and they can establish a client mesh network with mesh routers and other mesh clients. Wireless personal area networks (WPANs), wireless metropolitan area networks (MAN), Ad hoc networks, and wireless local area networks (WLANs) are expected to benefit from WMNs, which are expected to overcome restrictions and considerably increase performance. These networks provide wireless services to various applications in metropolitan locations, local, campus, and personal.

Wireless networks have advanced at a breakneck pace, inspiring a slew of new deployments. Around the world, research has increased, and numerous companies have already released products to the market, while others have begun to implement these networks in several application situations. Despite recent developments in wireless mesh networking, there are still several research difficulties to overcome. Worldwide, research is being carried out at a breakneck pace, with many articles already published in the literature, and the race to enhance this technology is continuing.

The book goes through each mesh layer's functionality, as well as existing algorithms and protocols.

Each chapter aims to show readers what is now accessible and how these networks might be enhanced and progressive by highlighting open research issues. The first chapter provides an overview of WMNs, such as essential design elements, characteristics, network architectures, and common application situations. In chapter 2, advanced physical methods for WMNs are covered, including adaptive coding and modulation, multi-radio systems, multi-channel systems, multiantenna systems, and software radios. In chapter 3, several medium access control (MAC) protocols for WMNs are presented and compared, ranging from multiple multi-channel MAC protocols, TDMA-based

MAC, CDMA-based MAC, and carrier-sense multi-access with collision avoidance (CDMA/CA) variations.

The routing protocols for WMNs are covered in Chapter 4. Different WMN routing metrics are examined and compared. Various types of routing protocols are also discussed. The fundamentals of numerous basic transport protocols are introduced in Chapter 5, followed by examining various transport protocols proposed for multi-hop wireless networks, including WMN. The security issues are discussed in Chapter 6. The security methods defined in IEEE 802.16 and 802.11 are offered first, afterward a thorough examination of security protocols for wireless mesh networks (WMNs) and ad hoc networks.

Different methods for managing and controlling WMNs are discussed in Chapter 7, including power management, topology management, network synchronization, and mobility management. The capacity analysis is the subject of Chapter 8. Diverse analytical methods for calculating wireless network capacity are discussed, as well as different capacity bounds. For WMNs, the existing capacity bounds are also reviewed, as well as their benefits and drawbacks.

We realized that this is the time to publish this book, which is aimed at teaching graduate students, motivating them for novel research ideas, and giving industry and academic experts with in-depth understanding and a detailed overview of the state-of-the-art in wireless mesh networking and representing how they can advance it, after working closely with engineers, researchers, and students. The book will fill a void in the literature by providing a complete overview of all study findings on this topic available in the last few years.

—Author

Chapter 1

Basics of Wireless Mesh Networks

CONTENTS

1.1. INTRODUCTION

Wireless mesh networks (WMNs) are a vital technology that has recently evolved as diverse wireless networks progress into the next generation to deliver improved services (Wang et al., 2007; Misra et al., 2009). Mesh clients and mesh routers make up the nodes in WMNs. Every node serves as a router as well as a host, promoting packets on behalf of other nodes that are not in the direct wireless transmission range of their destinations. A WMN is dynamically self-configured and self-organized, with the network's nodes automatically creating and sustaining mesh connectivity. This feature provides WMNs with several benefits, including consistent service coverage, ease of network maintenance, robustness, and inexpensive initial costs.

Common nodes with wireless NICs (network interface cards), such as PDAs, laptops, desktops, phones, and PocketPCs, can connect directly to wireless mesh routers. Customers deprived of wireless NICs can connect to wireless mesh routers through Ethernet. As a result, WMNs will considerably assist users in staying connected at all times, everywhere (Maolin, 2009). Furthermore, mesh routers' gateway capabilities allow WMNs to be integrated with a variety of existing wireless networks, including wireless-fidelity (Wi-Fi) systems, wireless sensor networks (WSNs), cellular systems, for microwave access international interoperability (WiMAX), and WiMedia. As a result of the integrated WMN, users of present networks can access services that would otherwise be unavailable (Lim et al., 2005; Muthaiah and Rosenberg, 2008).

For several applications, WMN is a useful technology such as neighborhood and community networks, broadband home networking, and building automation. It is getting a lot of popularity as a method for cash-strapped ISPs (Internet service providers), carriers, and more to build out robust and reliable wireless broadband service access with low upfront costs (Amaldi et al., 2008). WMNs may be deployed progressively, one node at a time, as required, thanks to their self-configuration and self-organization capabilities. With the addition of more nodes, the dependability and connection available to all subscribers will improve.

It is not difficult to set up a WMN because all of the necessary components are now in place, such as IEEE 802.11 MAC protocol, ad hoc routing protocols, and WEP (wired equivalent privacy) security. Numerous firms have recognized the technology's potential and are now offering wireless mesh networking systems. In university research labs, some testbeds have been established. Nevertheless, significant research efforts are required to make a WMN the best it can be. The present routing and MAC protocols used to WMNs, for example, lack sufficient scalability; such as throughput reduces dramatically as the number of hops or nodes rises (Girgis et al., 2014). Present security systems may be successful against particular types of attacks, but they require a complete framework to protect against assaults at various protocol layers. Other networking protocols have similar issues. As a result, existing communication protocols from the application layer through the MAC, routing, transport, and physical levels must be examined and improved. In some cases, it is necessary to develop new protocols.

From the perspective of WMNs, researchers have begun to examine the protocol architecture of current wireless networks, including WSNs, ad hoc networks, and. IEEE 802.11 networks. New mesh networking specifications are also being developed by industry standards bodies. IEEE 802.16 IEEE 802.15, and IEEE 802.11 all have sub-working groups dedicated to developing new WMN standards (Vanhatupa et al., 2007; Zhou et al., 2007).

1.2. NETWORK ARCHITECTURE

Mesh clients and mesh routers are the two types of nodes that make up WMNs. A wireless mesh router has additional routing operations to back mesh networking, in addition to the routing capacity for repeater/gateway functions found in a traditional wireless router. By using multi-hop communications, a wireless mesh router may attain similar coverage as a traditional wireless network while using significantly less transmission power. In a multi-hop mesh setting, a mesh router's medium contact control protocol can be augmented with higher scalability (Akyildiz and Wang, 2005).

Despite these distinctions, mesh, and traditional wireless routers are typically constructed on the same hardware platform. Mesh routers, as depicted in Figure 1.1, can be developed using dedicated computer systems, such as embedded systems. They can be developed using computer systems for general-purpose, such as desktop PCs or laptop computers.

Mesh clients have all of the required mesh networking functionalities and can therefore act as a router in WMN. These nodes, on the other hand, lack gateway or bridge functionality. Furthermore, mesh clients typically contain one wireless interface. As a result, mesh client software and hardware can be substantially simpler than mesh router hardware and software. Mesh clients support a wider range of devices than mesh routers (Akyildiz et al., 2005). As indicated in Figure 1.2, they can be a PDA, pocket PC, laptop, BACnet controller, RFID reader, IP phone, and a variety of additional devices. Depending on the functioning of the nodes, the architecture of WMNs can be divided into three categories.

1.2.1. Infrastructure/Backbone WMNs

Figure 1.3 depicts the architecture, with solid and dashed lines indicating wired links and wireless. Mesh routers form an infrastructure for clients who join them in this sort of WMN.

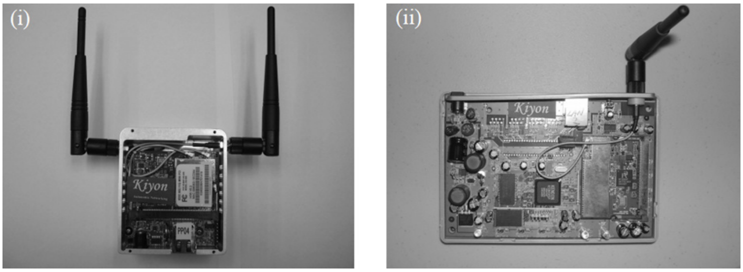

Figure 1.1. Examples of mesh routers based on different embedded systems: (i) PowerPC; (ii) ARM.

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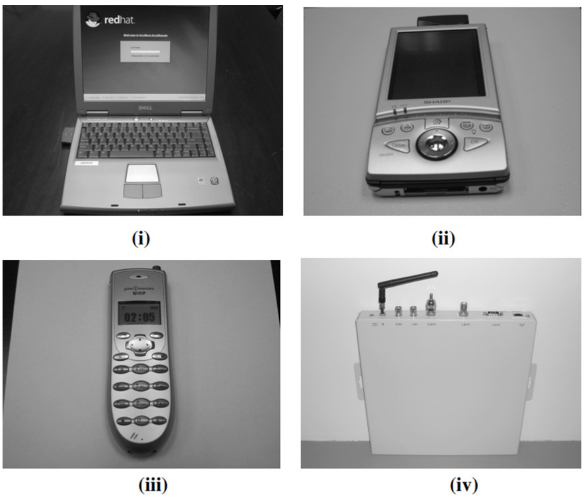

Figure 1.2. Examples of mesh clients: (i) laptop; (ii) PDA; (iii) Wi-Fi IP phone; (iv) Wi-Fi RFID reader.

Source: http://www.diva-portal.org/smash/get/diva2:306340/fulltext01.pdf.

Besides the widely used IEEE 802.11 technology, the WMN backbone/ infrastructure can be created utilizing a variety of radio technologies. The mesh routers create a network of self-healing, self-configuring links. Mesh routers with gateway capabilities can connect to the Internet. In mesh routers via gateway/bridge functionality, this technology, also known as infrastructure meshing, offers support for traditional clients and facilitates the addition of WMNs with current wireless networks (Al-Saadi et al., 2016). Ethernet links can attach traditional clients with Ethernet edges to mesh routers. Mesh routers can connect directly with conventional clients using a similar radio technology as mesh routers. With base stations, clients must connect that have Ethernet connections to mesh routers if multiple radio technologies are employed (Raniwala et al., 2004).

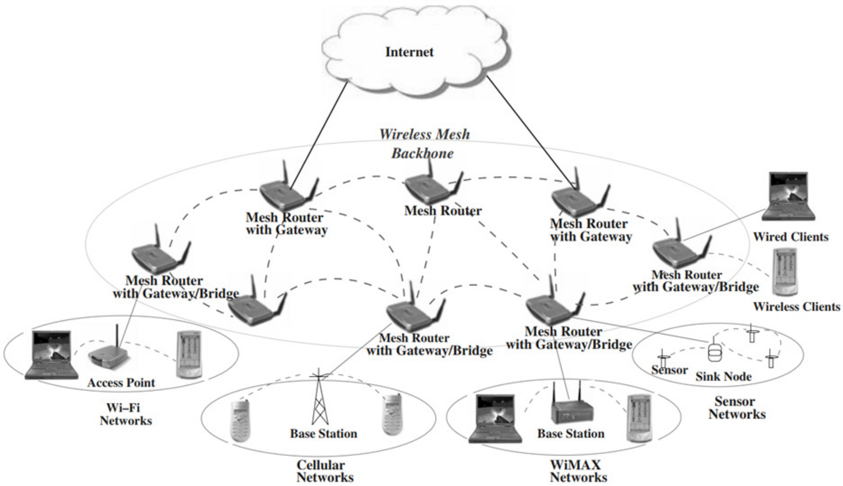

Figure 1.3. Infrastructure/backbone WMNs.

Source: https://www.researchgate.net/figure/Infrastructure-backbone-WMNs_fig1_266489187.

The most prevalent type is infrastructure/backbone WMNs. Infrastructure meshing, for example, can be used to create neighborhood and community networks. In a neighborhood, mesh routers are mounted on the rooftops of houses and can be used as contact points for customers in their hometowns and along the streets. In most routers, two types of radio are utilized, one for backbone communication and the other for user communication (Shahverdy et al., 2011). Long-range communication methods, such as directional antennas, can be employed to construct mesh backbone communication.

1.2.2. Client WMNs

Client meshing allows client devices to form peer-to-peer networks. Client nodes form the actual network in this design, which performs routing and configuration functions as well as supplying end-user applications to clienteles. As a result, a mesh router is not required for this network. Figure 1.4 depicts the fundamental architecture. A packet headed for a network node in a Client WMN bounces via numerous nodes to reach its endpoint (Sharma, 2012). Client WMNs are typically created using a single type of radio equipment. Furthermore, in comparison to infrastructure meshing, the demands on end-user devices are higher because, in Client WMNs, end users must undertake extra functions like self-configuration and routing (Raza et al., 2014).

1.2.3. Hybrid WMNs

As demonstrated in Figure 1.5, this architecture combines client meshing and infrastructure. Mesh clients can connect to the network via mesh routers or by meshing directly with further mesh clients. Whereas the infrastructure connects the WMN to further networks including the cellular, Wi-Fi, WiMAX, internet, and clients' routing, sensor networks' abilities improve coverage and connectivity within the WMN (Sakamoto et al., 2019).

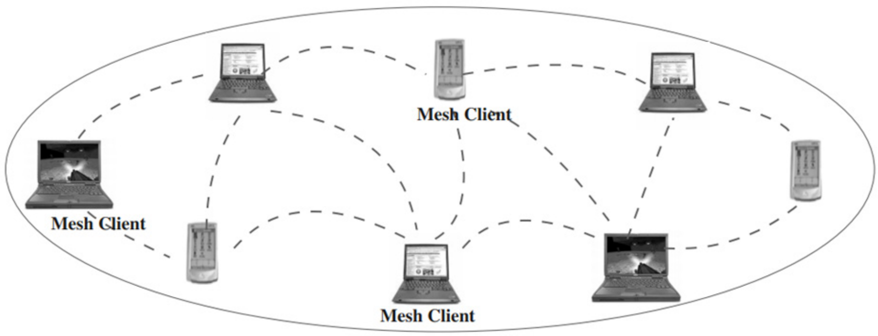

Figure 1.4. Client WMNs.

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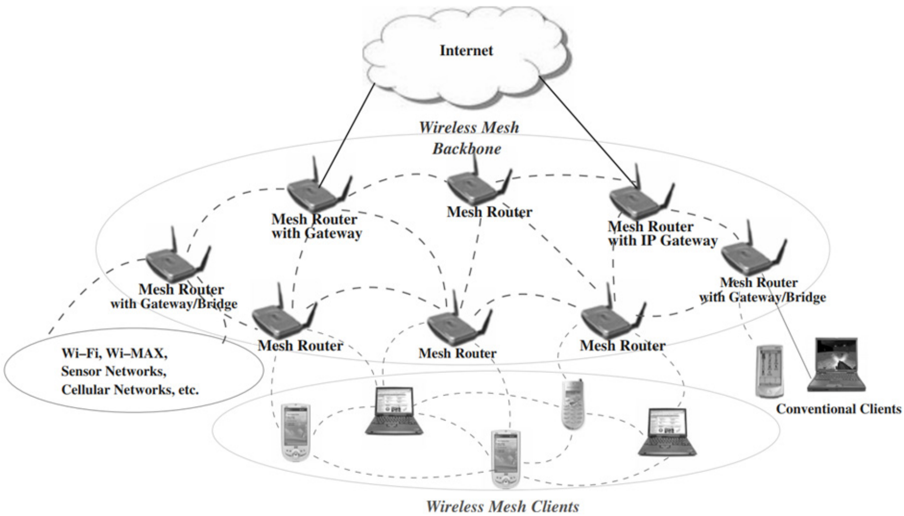


Figure 1.5. Hybrid WMNs.

Source: https://www.sciencedirect.com/science/article/abs/pii/S1389128604003457.

1.3. CHARACTERISTICS OF WIRELESS MESH NETWORKS (WMNS)

The features of WMNs are described in subsections.

1.3.1. Multihop Wireless Network

One reason for developing WMNs is to increase the range of present wireless networks without reducing channel dimensions. Another important goal of WMNs is to enable NLOS (non-line-of-sight) access to users who do not have direct LOS (line-of-sight) connections. Mesh-style multi hopping is required to achieve these objectives, as it allows for increased throughput deprived of reducing effective radio variety due to shorter link distances, reduced interference among nodes, and more effective frequency recycle (Sakamoto et al., 2018).

1.3.2. Support for Ad Hoc Networking, and Capability of Self-Forming, Self-Healing, and Self-Organization

Flexible network architecture, configuration, and easy deployment, fault tolerance, and mesh linking, such as multipoint-to-multipoint infrastructures, are all advantages of ad hoc networking. Because of these characteristics, WMNs require little initial investment and can scale up as required (Gopalan et al., 2013).

1.3.3. Mobility Dependence on the Type of Mesh Nodes

Mesh routers are typically immobile; however, mesh clients can be either fixed or mobile nodes. As a result, unlike ad hoc networks, the mobility in WMNs varies from node to node.

1.3.4. Multiple Types of Network Access

Backhaul connectivity to the Internet as well as P2P (peer-to-peer) communications in WMNs are both supported in WMNs (Wen and Hung, 2015). WMNs can also be used to integrate WMNs with further wireless systems and to give services to the end-users of these networks. An ad hoc network, on the other hand, does not require these features.

1.3.5. Dependence of Power-Consumption Constraints on the Type of Mesh Nodes

In most WMNs, mesh routers do not have tight power consumption limitations. Mesh clients, on the other hand, may need power-saving protocols. A mesh-capable sensor, for example, necessitates low-power communication protocols. Because power efficiency is the key priority for WSNs, MAC or routing protocols intended for mesh routers may not be acceptable for mesh clients (Gendron et al., 2016).

1.3.6. Compatibility and Interoperability with Existing Wireless Networks

For instance, WMNs based on IEEE 802.11 technology should comply with IEEE 802.11 values by supporting both traditional Wi-Fi and mesh-capable clients (Guy and Tabany, 2013). Further wireless networks, such as cellular, ZigBee, and WiMAX systems, must be interoperable with such WMNs.

Due to the lack of wired infrastructure that exists in Wi-Fi or cellular networks over the placement of access points or base stations, WMNs are typically considered to be a sort of ad hoc network. Although WMNs use ad hoc networking approaches, the additional abilities require more advanced processes and design values for WMNs to be realized (Masica, 2007). WMNs, rather than being a sort of ad hoc networking, seek to broaden the abilities of ad hoc networks. As a result, ad hoc networks can be thought of as a subgroup of WMNs. The distinctions among ad hoc and WMNs networks are discussed below to demonstrate this point. The mixed architecture is used in this analysis as it combines all of the benefits of WMNs.

1.3.7. Wireless Infrastructure/Backbone

As previously stated, WMNs are made up of mesh routers and wireless support. In the wireless sphere, the wireless mainstay gives robustness, connection, and vast coverage. Ad hoc network connectivity, on the other hand, is dependent on distinct performances from end-users, which may or may not be consistent (Varshney and Vetter, 2000).

1.3.8. Integration

Traditional clients that employ similar radio technology as a mesh router are supported by WMNs. This is performed using the host-routing feature found in mesh routers. In mesh routers, via bridge/gateway functionality, WMNs also allows the combination of many present networks like sensor, the Internet, cellular, and Wi-Fi networks. As a result of the utilization of wireless infrastructure, customers of a network can access facilities of other networks. Because the actual location of network nodes becomes less significant than network topology and capacity, joined wireless networks via WMNs look like the Internet backbone (Qiu et al., 2004).

1.3.9. Dedicated Routing and Configuration

End-user devices in ad hoc networks also conduct routine and set up for all other nodes in the network. WMNs, on the other hand, for these functions they have mesh routers. As a result, on end-user devices the load is reduced dramatically, resulting in high-end application abilities and lower energy usage for energy-constrained and mobile users. Furthermore, because end-user necessities are restricted, the charges of devices that can be employed in WMNs are reduced (Schaefer and Boche, 2014).

1.3.10. Multiple Radios

As explained earlier, to access functionalities and achieve routing mesh routers can be prepared with numerous radios. The separation of two principal types of traffic could be achieved through this in the wireless domain. Among the mesh routers, the configuration and routing traffic is achieved, via the end-users access to the network can be passed on a dissimilar radio. The capacity of the network could be improved through this. Instead, in a similar channel, these functionalities are made in ad hoc networks restricting the performance (Waharte et al., 2006).

1.3.11. Mobility

Because ad hoc networks rely on end-user devices for connectivity, network structure and routing are influenced by user movement. Routing protocols, along with network deployment and configuration, face new issues as a result. Because mesh routers supply the infrastructure of WMNs, the WMN's coverage can be simply constructed (Roy et al., 2008).

While providing continuous connectivity throughout the network, the mobility of end users is still supported, without compromising the performance of the network.

1.3.12. Compatibility

When compared to ad hoc networks, WMNs have a lot of differences. Ad hoc networks, on the other hand, might be measured as a subset of WMNs, as explained above. More particular, existing techniques developed for ad hoc networks can be used for WMNs as well. Multiple ad hoc networks, for example, can be handled in WMNs using mesh routers and routing capable end users, but with further network integration (Wang, 2008).

1.4. APPLICATION SCENARIOS

Through various applications the development and research of WMNs are inspired which proves the capable market, but, simultaneously, through further wireless networks, these applications cannot be reinforced directly like WSNs, ad hoc networks, cellular systems, typical IEEE 802.11, etc. In this part, we explain these applications (Teger and Teger, 2002).

1.4.1. Broadband Home Networking

Now via the IEEE 802.11 WLANs broadband home networking is apprehended. The position of the access points is an apparent problem. A home contains several dead zones deprived of service coverage, without a site survey.

Site survey solutions are costly and inconvenient for residential networking, and multiple access point installation is similarly costly and inconvenient due to Ethernet wire from access points to the backhaul network access hub or modem (Teger and Teger, 2002). Furthermore, communications among end nodes connected to two dissimilar access points must return to the access hub. This is not a viable option, particularly in the case of broadband networking.

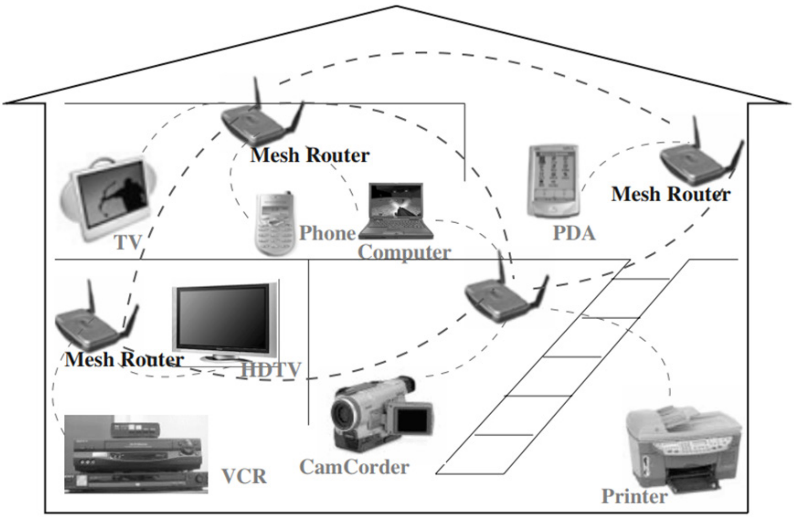


Figure 1.6. WMNs for broadband home networking.

Source: https://www.researchgate.net/figure/Short-Distance-Home-Mesh-Network_fig4_266260298.

All of these challenges in home networking can be resolved by mesh networking, as shown in Figure 1.6. Wireless mesh routers must be used to replace the access points, with mesh communication built between them. As a result, communication among these nodes develops far more adaptable and resilient to network and connection disruptions. Dead zones can be removed by the addition of moving mesh router locations, mesh routers, or automatically modifying mesh router power levels. Mesh networking allows for communication inside home networks without having to constantly return to the access hub. As a result, backhaul access-related network congestion can be avoided. Wireless mesh routers have no restrictions on mobility or power consumption in this application. As a result, procedures for WSNs and mobile ad hoc networks (MANETs) are too complex to provide acceptable work in this application (Zhang et al., 2001; Zahariadis et al., 2002). Wi-Fi, on the other hand, is unable to provide ad hoc multihop networking. As a result, WMNs are ideal for home networking via broadband.

1.4.2. Community and Neighborhood Networking

The standard design for network access in a community depends on a digital subscriber line (DSL) or cable connection to the Internet, with a wireless router connected to a cable or subscriber line modem as the final hop. This kind of network access has some disadvantages (Ennis and West, 2014):

- All traffic must portable via the Internet, even if the data must be exchanged inside a neighborhood or community. This results in a huge reduction in network resource use;
- Wireless services do not cover a major portion of the area between houses;
- Wireless services must be placed separately, and a costly but high-bandwidth gateway among several residences or neighborhoods may not be collective. Consequently, the cost of network services may rise;
- For home, to communicate or access the internet just a solo path might be available.

Via lithe mesh connectivity, the WMNs lessen the above-discussed drawbacks among homes, as depicted in Figure 1.7. Several applications like video streaming, distributed file storage, and distributed file access could be enabled through WMNs (Gilchrist, 2000).

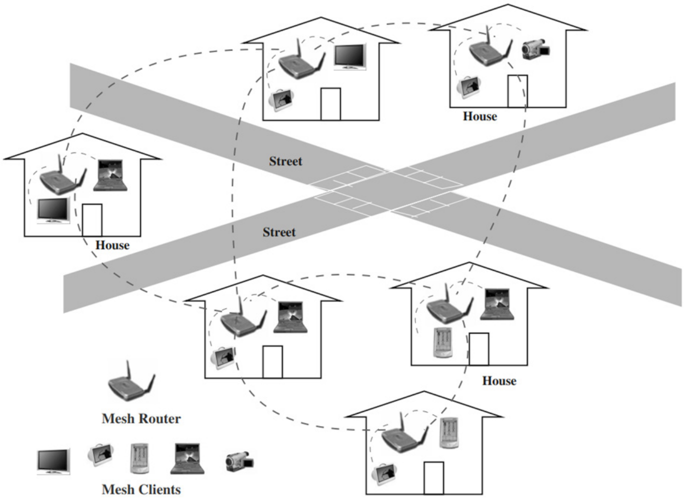


Figure 1.7. WMNs for community networking.

Source: https://slideplayer.com/slide/6521608/.

1.4.3. Enterprise Networking

It is a large-scale network between offices in several buildings or we can call it a medium-size network for all offices in a whole building, or a smaller network inside an office. Now the commonly used wireless networks are standard IEEE 802.11 in numerous offices. Nevertheless, these networks are yet remote islands. Via, wired Ethernet connections, the connections between them have to be attained, that is the main purpose for the costly of networks (Woodman et al., 1993). Furthermore, the addition of further backhaul access modems just rises capability locally, nevertheless, it does not increase strength to network congestion, link failures, and further issues of the whole enterprise network. The ethernet wires can be removed only if the contact points are substituted by mesh routers, as demonstrated in Figure 1.8. In the whole network, several backhaul access modems can be common through all nodes, and therefore advance the resource utilization and sturdiness of enterprise networks. With the increases in the size of the enterprise, the WMNs can easily raise (Lin and Lin, 1996).

For enterprise networking, the WMNs are very complex than at home as more complex network topologies and more nodes are employed. The amenity model of enterprise networking can be employed in several other commercial and public service networking situations for example convention centers, shopping malls, hotels, airports, sports centers, etc. (Ming et al., 1996).

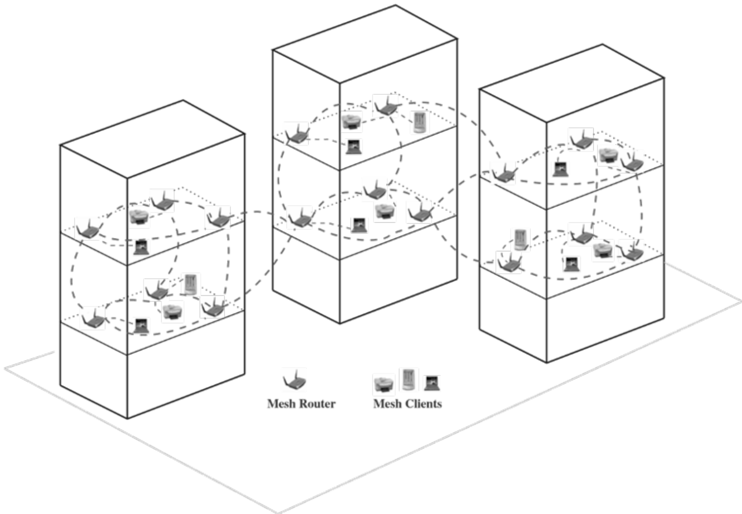


Figure 1.8. WMNs for enterprise networking.

Source: https://slideplayer.com/slide/4900465/.

1.4.4. Metropolitan Area Networks (MAN)

In a metropolitan area, the WMNs contain numerous advantages. In WMNs, the physical-layer transmission rate of a node is greater than that in cellular systems. For instance, at a rate of 54 Mbps, an IEEE 802.11g node can spread. Furthermore, in WMNs the communication among nodes does not depend on a strengthened backbone. Compared to strengthened networks, such as optical or cable networks, wireless mesh MAN is a cheap substitute for broadband networking, particularly in weak regions. The wireless mesh, metropolitan area networks (MAN) take on a possibly much greater area than building, enterprise, home, or community networks. Therefore, on the network scalability, the condition through wireless mesh MANs is very high than other applications (Yao et al., 2001).

1.4.5. Transportation Systems

Rather than restraining IEEE 802.16 or 802.11 access to stops and stations, mesh networking technology can be extended access into trains, ferries, and buses. Therefore, distant monitoring of in-vehicle security video, suitable passenger data services, and communications of the driver can be reinforced. Fa transportation system, to allow these mesh networking, two major methods are required: the highspeed mobile backhaul from a vehicle to the Internet, and mobile mesh networks inside the vehicle (Figures 1.9 and 1.10) (Mehmood et al., 2011).

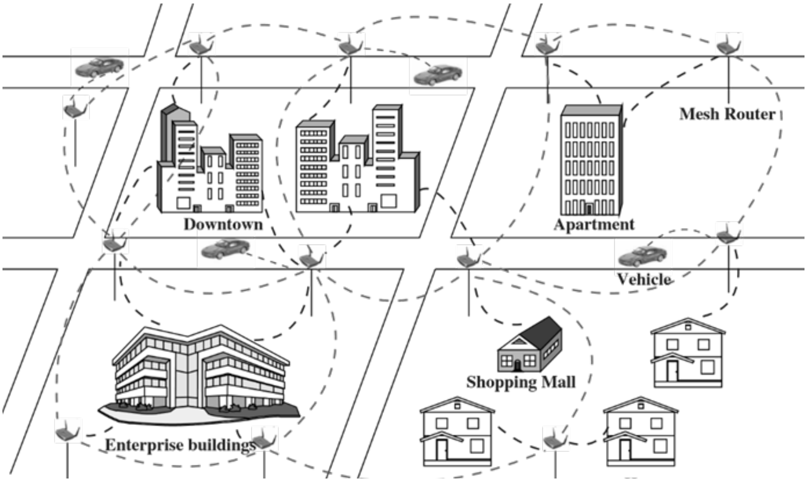


Figure 1.9. WMNs for metropolitan area networks.

Source: https://www.researchgate.net/figure/WMNs-for-Metropolitan-Area-Network_fig3_341243978.

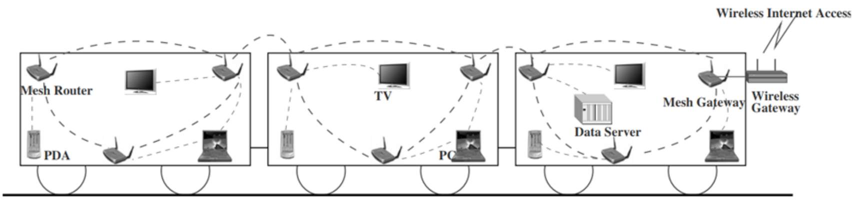


Figure 1.10. WMNs for transportation systems.

Source: https://onlinelibrary.wiley.com/doi/book/10.1002/9780470059616.

1.4.6. Building Automation

Various electrical devices in a structure, such as air conditioners, light, elevators, power, and so on, must be monitored and controlled. Now, this operation is carried out via traditional wired networks, which are exceedingly expensive to construct and maintain due to their complexity. Wi-Fi-based networks have recently been embraced to minimize the price of these networks (Teng et al., 2008). However, because the placement of Wi-Fi for this application is still fairly costly because of Ethernet wiring, this endeavor has not yet yielded sufficient results. The deployment cost will be greatly decreased if BACnet (Building Automation and Control networks) access points are replaced with mesh routers, as shown in Figure 1.11. Because of the mesh connectivity among wireless routers, the deployment process is also considerably easier.

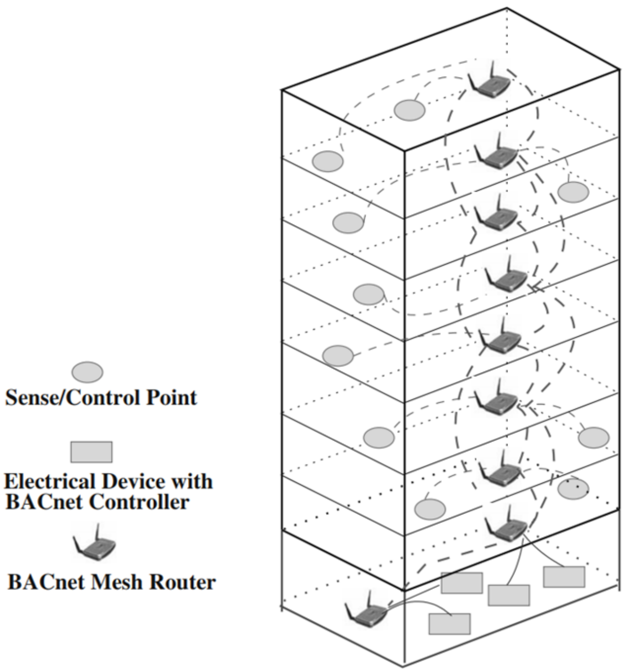


Figure 1.11. WMNs for building automation.

Source: https://slidetodoc.com/wireless-mesh-networks-by-cunqing-hua-the-notes/.

1.4.7. Health and Medical Systems

Diagnosis and monitoring data must be managed and sent from one room to another in a medical center or hospital for a variety of reasons. Because high-resolution medical images and varied periodic monitoring data can readily provide a persistent and significant volume of data transmission is frequently broadband (Mehmood et al., 2011). Traditional wired networks can just give fixed medical devices limited network connectivity. Wi-Fi-based networks should depend on the presence of Ethernet connections, which can increase system complexity and cost while leaving dead spots unavoidable. These problems, on the other hand, do not occur with WMNs.

1.4.8. Security Surveillance Systems

Security surveillance systems have become a need for malls, retail, supermarket stores, company buildings, and other places where security is a major alarm. WMNs are a feasible solution than wired networks for connecting all devices to deploy such systems as needed. Because still videos and photos make up the majority of network traffic, this application necessitates significantly more network bandwidth than further applications (Gao et al., 2007).

WMNs can also be used for P2P communications and impulsive networking, in addition to the applications listed above. Wireless networks for firefighters and an alternative response team, for example, do not know where they will be deployed in advance. A WMN can be readily constructed by simply putting wireless mesh routers in desirable areas. P2P communication anyplace anytime is an efficient option for information sharing for a group of individuals who have devices with wireless networking capabilities, such as PDAs and laptops. These examples show that WMNs are a subset of ad hoc networks and can thus perform all of the functions that ad hoc networking can (Belkhouja et al., 2018).

1.5. CRITICAL DESIGN FACTORS

Factors that have a significant impact on a network's performance must be considered before it is planned, deployed, and operated. The important factors for WMNs are summarized as follows.

1.5.1. Radio Techniques

Wireless radios have experienced a considerable transformation as a result of rapid advancements in semiconductors, communication theory, and RF. Many techniques to increasing the flexibility and capacity of wireless systems have been presented recently. Multiradio systems, MIMO systems, and smart antennas and directional are all good examples. MIMO is now one of the major knowhows for IEEE 802.11n, the great-speed Wi-Fi expansion. There are development platforms and multi-radio chipsets on the market (Han et al., 2011).

Very advanced radio technologies, like frequency-agile/cognitive radios, reconfigurable radios, and also software radios, have been employed in wireless communication to increase the performance of wireless radio and control by upper-layer protocols (Sharma et al., 2015). Though these radio technologies are yet in their beginning, because of their ability to vigorously controlling the radios they are likely to be the future platform for wireless networks. All of these advanced wireless radio methods necessitate a ground-breaking design in higher layer protocols, particularly routing protocols, and MAC.

When directional antennas are used in IEEE 802.11 networks, for example, a routine procedure must account for the assortment of directional antenna parts. Although directional antennas can lower the number of exposed nodes, they also increase the number of concealed nodes. As a result, MAC protocols must be changed to address this problem. New MAC protocols are also required for MIMO systems (Evans, 1963). Much more powerful MAC protocols, like programmable MAC, are expected when software radios are considered.

1.5.2. Scalability

In WMNs, multi-hop communication is widespread. Communication techniques for multihop networking are widely known to suffer from scalability concerns, which means that as the size of the network grows, network performance suffers dramatically (Correia et al., 2010). Routing protocols may be unable to discover a reliable routing path, transport protocols may lose connections, and MAC protocols may see a considerable loss in throughput. As an example, when the amount of hops is increased to 4 or more, the present IEEE 802.11 MAC procedure and its byproducts cannot reach a decent performance. The cause for the low scalability is that when the network scales up, the end-to-end reliability reduces dramatically.

Because of their ad hoc construction, in WMNs, the central multiple access schemes like code division multiple access (CDMA) and time division multiple access (TDMA) are hard to Accenture because of their difficulties, and for TDMA a universal requirement on timing synchronization. Accurate clock synchronization within the global network is challenging to establish in a dispersed multihop network (Chen et al., 2011). As a result, distributed multiple access methods like carrier sense multiple access with collision avoidance (CA) are better. However, CSMA/CA has a poor frequency spatial-reuse efficiency limiting the scalability of CSMA/CA-based multihop networks substantially. Designing hybrid multiple access strategies with CDMA and TDMA or CSMA/CA to improve the scalability of WMNs is a fascinating and demanding research topic.

1.5.3. Mesh Connectivity

Mesh connection, which is a vital condition on protocol design, notably for routing protocols and MAC, is the source of many advantages of WMNs. Algorithms for network topology control and self-organization are frequently required. WMN performance can be considerably improved by using topology-aware MAC and routing protocols (Isenburg, 2002).

1.5.4. Broadband and QoS

Unlike other ad hoc networks, the majority of WMN applications are broadband services with varying Quality of Service (QoS) needs. As a result, communication protocols must evaluate other performance parameters like per-node throughput, aggregate, and, delay jitter, and packet loss ratios in addition to end-to-end transmission time and equality.

1.5.5. Compatibility and Interoperability

Supporting network connectivity for both mesh and conventional clients is a wanted feature for WMNs. As a result, WMNs must be backward companionable with traditional client nodes; otherwise, the incentive to install WMNs will be severely harmed. Certain mesh routers must be capable of interoperation between heterogeneous wireless networks to integrate WMNs with other wireless networks (Lee et al., 2002).

1.5.6. Security

Because of a lack of encouragement from users to subscribe to dependable services, WMNs will not be able to succeed without a convincing security solution. Although various security techniques for wireless LANs have been developed, they are not yet prepared for WMNs. Because of the distributed system construction, there is no central reliable authority to issue a general key in a WMN. Existing security systems for ad hoc networks can be used for WMNs, but there are a few concerns to consider (Li et al., 2013).

- The majority of security solutions for ad hoc networks are still in their infancy and cannot be used in practice;
- From that of a traditional ad hoc network, the network building of WMNs differs, resulting in security procedures that are different.

As a result, new security methods must be created, including encryption techniques, secure MAC and routing protocols security key distribution, security monitoring, and intrusion detection.

1.5.7. Ease of Use

Protocols must be intended to make the network as autonomous as feasible, with dynamic topology control, self-organization, automatic power management, flexibility to a momentary connection failure, and a rapid network subscription/user verification technique. Furthermore, network management tools must be advanced to proficiently preserve WMN operations, monitor recital, and configure parameters. These techniques, together with autonomic processes in protocols, allow WMNs to be deployed quickly (Li et al., 2013).

REFERENCES

1. Aivaloglou, E., & Gritzalis, S., (2010). Hybrid trust and reputation management for sensor networks. *Wireless Networks*, *16*(5), 1493–1510.
2. Akyildiz, I. F., & Wang, X., (2005). A survey on wireless mesh networks. *IEEE Communications Magazine*, *43*(9), 523–530.
3. Akyildiz, I. F., Wang, X., & Wang, W., (2005). Wireless mesh networks: A survey. *Computer Networks*, *47*(4), 445–487.
4. Al-Saadi, A., Setchi, R., Hicks, Y., & Allen, S. M., (2016). Routing protocol for heterogeneous wireless mesh networks. *IEEE Transactions on Vehicular Technology*, *65*(12), 9773–9786.
5. Amaldi, E., Capone, A., Cesana, M., Filippini, I., & Malucelli, F., (2008). Optimization models and methods for planning wireless mesh networks. *Computer Networks*, *52*(11), 2159–2171.
6. Belkhouja, T., Du, X., Mohamed, A., Al-Ali, A. K., & Guizani, M., (2018). Symmetric encryption relying on chaotic henon system for secure hardware-friendly wireless communication of implantable medical systems. *Journal of Sensor and Actuator Networks*, *7*(2), 21.
7. Chen, Y., Zhang, S., Xu, S., & Li, G. Y., (2011). Fundamental trade-offs on green wireless networks. *IEEE Communications Magazine*, *49*(6), 30–37.
8. Correia, L. M., Zeller, D., Blume, O., Ferling, D., Jading, Y., Gódor, I., & Van Der Perre, L., (2010). Challenges and enabling technologies for energy aware mobile radio networks. *IEEE Communications Magazine*, *48*(11), 66–72.
9. Ennis, G., & West, D., (2014). Community development and umbrella bodies: Networking for neighborhood change. *British Journal of Social Work*, *44*(6), 1582–1601.
10. Evans, S., (1963). Radio techniques for the measurement of ice thickness. *Polar Record*, *11*(73), 406–410.
11. Gao, T., Massey, T., Selavo, L., Crawford, D., Chen, B. R., Lorincz, K., & Welsh, M., (2007). The advanced health and disaster aid network: A light-weight wireless medical system for triage. *IEEE Transactions on Biomedical Circuits and Systems*, *1*(3), 203–216.
12. Gendron, B., Scutellà, M. G., Garroppo, R. G., Nencioni, G., & Tavanti, L., (2016). A branch-and-Benders-cut method for nonlinear

power design in green wireless local area networks. *European Journal of Operational Research*, *255*(1), 151–162.

13. Gilchrist, A., (2000). The well-connected community: Networking to the edge of chaos. *Community Development Journal*, *35*(3), 264–275.
14. Girgis, M. R., Mahmoud, T. M., Abdullatif, B. A., & Rabie, A. M., (2014). Solving the wireless mesh network design problem using genetic algorithm and simulated annealing optimization methods. *International Journal of Computer Applications*, *96*(11), 4–19.
15. Gopalan, S. M., Thiyagarajan, M., Manavalan, U., & Baladubramanian, P., (2013). Cross layer interaction for improving the performance of TCP in multihop wireless networks. *Arab Gulf Journal of Scientific Research*, *31, 1–9*.
16. Guy, C. G., & Tabany, M. R., (2013). LTE and LTE-A interworking and interoperability with 3GPP and non-3GPP wireless networks. *Journal of Emerging Trends in Computing and Information Sciences*, *4*(8), 649–656.
17. Han, C., Harrold, T., Armour, S., Krikidis, I., Videv, S., Grant, P. M., & Hanzo, L., (2011). Green radio: Radio techniques to enable energy-efficient wireless networks. *IEEE Communications Magazine*, *49*(6), 46–54.
18. Isenburg, M., (2002). Compressing polygon mesh connectivity with degree duality prediction. *Graphics Interface*, *2*, 161–170.
19. Lee, H., Alliez, P., & Desbrun, M., (2002). Angle-analyzer: A triangle-quad mesh codec. *Computer Graphics Forum*, *21*(3), 383–392.
20. Li, S., Zhao, S., Wang, X., Zhang, K., & Li, L., (2013). Adaptive and secure load-balancing routing protocol for service-oriented wireless sensor networks. *IEEE Systems Journal*, *8*(3), 858–867.
21. Lim, A., Rodrigues, B., Wang, F., & Xu, Z., (2005). k-Center problems with minimum coverage. *Theoretical Computer Science*, *332*(1–3), 1–17.
22. Lin, P., & Lin, L., (1996). Security in enterprise networking: A quick tour. *IEEE Communications Magazine*, *34*(1), 56–61.
23. Maarouf, I., Baroudi, U., & Naseer, A. R., (2009). Efficient monitoring approach for reputation system-based trust-aware routing in wireless sensor networks. *IET Communications*, *3*(5), 846–858.

24. Maolin, T. A. N. G., (2009). Gateways placement in backbone wireless mesh networks. *Int'l J. of Communications, Network, and System Sciences*, *2*(01), 44.
25. Masica, K., (2007). Recommended practices guide for securing ZigBee wireless networks in process control system environments. *Lawrence Livermore National Laboratory*, *2*(1), 6–8.
26. Mehmood, R., & Alturki, R., (2011). A scalable multimedia QoS architecture for ad hoc networks. *Multimedia Tools and Applications*, *54*(3), 551–568.
27. Mehmood, R., Alturki, R., & Zeadally, S., (2011). Multimedia applications over metropolitan area networks (MANs). *Journal of Network and Computer Applications*, *34*(5), 1518–1529.
28. Ming, W., Song, J., Rui, Y., & Yingcai, B., (1996). The integration of large-scale enterprise networking environment. *Journal-Shanghai Jiaotong University*, *30*, 120–125.
29. Misra, S., Misra, S. C., & Woungang, I., (2009). *Guide to Wireless Mesh Networks*, *9*(9), 3–10.
30. Muthaiah, S. N., & Rosenberg, C., (2008). Single gateway placement in wireless mesh networks. *Proc. ISCN*, *8*, 4754–4759.
31. Qiu, L., Chandra, R., Jain, K., & Mahdian, M., (2004). *Optimizing the Placement of Integration Points in Multi-Hop Wireless Networks, 4*, 271–282.
32. Raniwala, A., Gopalan, K., & Chiueh, T. C., (2004). Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, *8*(2), 50–65.
33. Raza, B., Qaiser, F., & Raza, M. A., (2014). Study of routing protocols in wireless mesh networks. *University, Multan, Pakistan*, *3*(2), 19–26.
34. Rezgui, A., & Eltoweissy, M., (2008). µRACER: A reliable adaptive service-driven efficient routing protocol suite for sensor-actuator networks. *IEEE Transactions on Parallel and Distributed Systems*, *20*(5), 607–622.
35. Roy, S., Koutsonikolas, D., Das, S., & Hu, Y. C., (2008). High-throughput multicast routing metrics in wireless mesh networks. *Ad Hoc Networks*, *6*(6), 878–899.
36. Sakamoto, S., Ozera, K., Barolli, A., Ikeda, M., Barolli, L., & Takizawa, M., (2019). Implementation of an intelligent hybrid simulation systems

for WMNs based on particle swarm optimization and simulated annealing: Performance evaluation for different replacement methods. *Soft Computing*, *23*(9), 3029–3035.

37. Sakamoto, S., Ozera, K., Ikeda, M., & Barolli, L., (2018). Implementation of intelligent hybrid systems for node placement problem in WMNs considering particle swarm optimization, hill climbing and simulated annealing. *Mobile Networks and Applications*, *23*(1), 27–33.
38. Schaefer, R. F., & Boche, H., (2014). Physical layer service integration in wireless networks: Signal processing challenges. *IEEE Signal Processing Magazine*, *31*(3), 147–156.
39. Shahverdy, M., Behnami, M., & Fathy, M., (2011). A new paradigm for load balancing in WMNs. *International Journal of Computer Networks (IJCN)*, *3*(4), 239–246.
40. Sharma, P., (2012). Performance comparison of routing protocols in WMNS. *International Journal of Information Technology and Knowledge Management December 2012*, *6*(1), 83–88.
41. Sharma, S. K., Bogale, T. E., Chatzinotas, S., Ottersten, B., Le, L. B., & Wang, X., (2015). Cognitive radio techniques under practical imperfections: A survey. *IEEE Communications Surveys & Tutorials*, *17*(4), 1858–1884.
42. Srinivasan, A., & Wu, J., (2009). Secure and reliable broadcasting in wireless sensor networks using multi-parent trees. *Security and Communication Networks*, *2*(3), 239–253.
43. Teger, S., & Waks, D. J., (2002). End-user perspectives on home networking. *IEEE Communications Magazine*, *40*(4), 114–119.
44. Teng, X. F., Zhang, Y. T., Poon, C. C., & Bonato, P., (2008). Wearable medical systems for p-health. *IEEE Reviews in Biomedical Engineering*, *1*, 62–74.
45. Vanhatupa, T., Hannikainen, M., & Hamalainen, T. D., (2007). Genetic algorithm to optimize node placement and configuration for WLAN planning. In: *2007 4th International Symposium on Wireless Communication Systems* (Vol. 6, No. 1, pp. 612–616).
46. Varshney, U., & Vetter, R., (2000). Emerging mobile and wireless networks. *Communications of the ACM*, *43*(6), 73–81.
47. Waharte, S., Boutaba, R., Iraqi, Y., & Ishibashi, B., (2006). Routing protocols in wireless mesh networks: challenges and design considerations. *Multimedia tools and Applications*, *29*(3), 285–303.

48. Wang, J., Xie, B., Cai, K., & Agrawal, D. P., (2007). Efficient mesh router placement in wireless mesh networks. In: *2007 IEEE International Conference on Mobile Ad Hoc and Sensor Systems* (Vol. 4, No. 3, pp. 1–9).
49. Wang, K., Bai, X., Li, J., & Ding, C., (2010). A service-based framework for pharmacogenomics data integration. *Enterprise Information Systems*, *4*(3), 225–245.
50. Wang, X., (2008). Wireless mesh networks. *Journal of Telemedicine and Telecare*, *14*(8), 401–403.
51. Wen, Y. F., & Hung, K. Y., (2015). Energy efficiency heterogeneous wireless access selection for multiple types of applications. *Journal of Systems and Software*, *101*, 97–109.
52. Woodman, C., Rybczynski, T., Ellis, J., & Black, B., (1993). A new paradigm for enterprise networking. In: *Proceedings of ICC'93-IEEE International Conference on Communications* (Vol. 1, pp. 91–95).
53. Yao, S., Yoo, S. B., Mukherjee, B., & Dixit, S., (2001). All-optical packet switching for metropolitan area networks: opportunities and challenges. *IEEE Communications Magazine*, *39*(3), 142–148.
54. Zahariadis, T., Pramataris, K., & Zervos, N., (2002). A comparison of competing broadband in-home technologies. *Electronics & Communication Engineering Journal*, *14*(4), 133–142.
55. Zhang, H., Udagawa, T., Arita, T., Tsuji, J., Okada, K., Sasase, I., & Nakagawa, M., (2001). Wireless 1394: A new standard for integrated wireless broadband home networking. In: *IEEE VTS 53rd Vehicular Technology Conference, Spring 2001; Proceedings* (Vol. 2, pp. 1124–1128).
56. Zhang, T., Yang, K., & Chen, H. H., (2009). Topology control for service-oriented wireless mesh networks. *IEEE Wireless Communications*, *16*(4), 64–71.
57. Zhang, X., & Su, H., (2009). Network-coding-based scheduling and routing schemes for service-oriented wireless mesh networks. *IEEE Wireless Communications*, *16*(4), 40–46.
58. Zhou, P., Manoj, B. S., & Rao, R., (2007). A gateway placement algorithm in wireless mesh networks. In: *Proceedings of the 3rd International Conference on Wireless Internet* (Vol. 3, No. 1, pp. 1–9).

Chapter 2

Mesh Terminology and Overview

CONTENTS

2.1. INTRODUCTION

The Internet has become an integral component of our daily lives. Many basic operations, such as supermarket, banking, and gift buying, and buying travel or movie tickets, are now done online. Furthermore, we are getting an increasing amount of our amusement from online sources: social networking and entertainment are some of the fastest-growing industries (Ahmed and Aslani, 2014). We have witnessed the emergence of basic video quality from sites like YouTube, as well as the growth of social networking platforms like Facebook and My Space, that has exploded in popularity, particularly among new generations of customers. As we remain on our current path of performing much online, our bandwidth requirements will grow. In the future, we may anticipate being able to produce significant material for upload to the Internet and also continuing to download material. Yet that is not; all our demand for Internet access and quality will rise as well (Zhu et al., 2015).

It will be extremely convenient when future access to the Internet was also wireless, only with the near-ubiquitous service that we have come to expect with cellular phones. Yet, constructing a fresh network or updating an old network to accommodate this would need the installation or modification of a significant amount of infrastructure. What if it was a way to get better Internet access with fewer requirements? This is frequently marketed as the mesh network's domain.

2.2. WHAT EXACTLY IS A MESH?

It is probably simplest to start looking into mesh networks by going backward and studying how wireless and cellular local area networks (LANs) function before focusing on the mesh approach's similarities and distinctions (Komenda et al., 2015).

The cellular network, as the name implies, is made up of numerous radio coverage cells, every with a base station in the center that broadcasts radio signals across a large region, such as many kilometers. The consumer's device is a tiny portable gadget with fewer features and functions as compared to the base station. In which cell's coverage drops down, nearby cells take up the slack. The cells honeycomb covers a huge area in this way. Certainly, the assurance of uninterrupted coverage is a benefit. This is a significant benefit, however, there are also drawbacks: a fresh network should be designed, as well as the cell sites must ideally be deployed concurrently across the entire coverage area, however, this entails a significant upfront expense for the operator (Zanten et al., 2009).

Despite our best efforts, black patches sometimes occur when the customer's radio signal is blocked by an object. While adding another tiny cell would be one method to get around this, doing so would raise the expense of network equipment and hence have a negative impact on the operator's economic model. A compromise is reached whereby normal network accessibility is near 100%, however, does not ensure that everyone will be satisfied all of the time (Jun and Sichitiu, 2003).

Choosing a carrier frequency that propagates effectively along with a variety of terrain kinds and has acceptable building penetration properties is the main approach utilized to assure adequate coverage. This will improve capacity and coverage while reducing the cells number used.

It is no accident, therefore, as cellular networks all around the world use the same frequency range. In most nations, that spectrum is highly prized and has already been allocated. It is important to remember that cellular networks were created largely for communications of voice that are inherently burst. As a result, the spectrum amount they have is not optimal for current multimedia communications that may include the transmission of delay-sensitive information over a lengthy period, such as while watching a movie. As a result, cellular systems will evolve in the future to better accommodate applications of multimedia (Zhang and Mukheriee, 2004).

Next, let us take a look at the state of wireless LANs. As the name implies, a wireless LAN is primarily concerned with coverage of a local area. The goal is generally to encompass a business or a residence. Typically, wireless LANs are designed to span up to a 100-meter radius surrounding a wired LAN's wireless access point. Although the concepts of a base station and access point are identical, the distances that must be considered are significantly divergent. One obvious advantage is that the sort of spectrum needed is distinct, and thus the propagation properties for wireless LANs do not require to be as excellent. Because high frequencies are sufficient to traverse smaller distances, as a result, wireless LANs often operate at higher frequencies than cellular networks (Xie and Wang, 2008). The spectrum is in lower demand here. In reality, most wireless LANs run in a spectrum that is not subject to a license, lowering system costs. Non-licensed wireless LANs, unlike cellular networks, do not have any exclusive usage of their spectrum, therefore this is a sword of double-edged. As a result, the wireless LAN must be designed to tolerate interference that comes at a cost in terms of system efficiency and equipment. Congestion can reduce efficiency to zero in the extreme, as it does in any unregulated system (Zhang and Mukheriee, 2004).

The wireless LAN may indeed be easier to set up than that of a cellular system for a minimum of two additional reasons. Generally, a wireless LAN has no idea of hand-over from cell to cell, neither does it provide substantially greater than an actual data link among customers; it is up to supplementary protocols like TCP and IP to establish routes and effectively transport data. It is important to mention that wireless LANs were created mainly for data transmission rather than speech transmission. Therefore, a design restriction was imposed for conveying bursty data that was reasonable at the moment (Chowdhury and Akyildiz, 2008). This implies that, although wireless LANs can handle enormous quantities of data, they are frequently unable to cope with current multimedia communications. To put it another way, while wireless LANs were intended especially for situations when demand is greater during peak periods, these peak times were not supposed to last very long. Much to the evolution of cellular systems roadmap, the upcoming evolution of wireless LAN technologies is currently focused on greater compatibility for multimedia applications (Hou et al., 2008).

Finally, when it comes to a mesh network, its primary operating characteristic may be deduced out of its name. Consider the web spiders, Figure 2.1, or even the grid layout of streets in a central area as examples of meshes in many forms. Assume that there is a node at every substance junction. To our needs, these instances have two things in common (Pahlavan and Levesque, 1994):

- Anyone else node may be reached by traveling a series of intermediate nodes; and
- There is no primary node.

A mesh design is distinguishable from a wireless or cellular LAN design. There is also no centrally controlled because all nodes are equivalent, consequently, every node should participate actively in networking and be a sink or source of traffic. Multi-hopping between nodes, instead of a single hop to the base, has to be a common capacity (Eckhardt and Steenkiste, 1999).

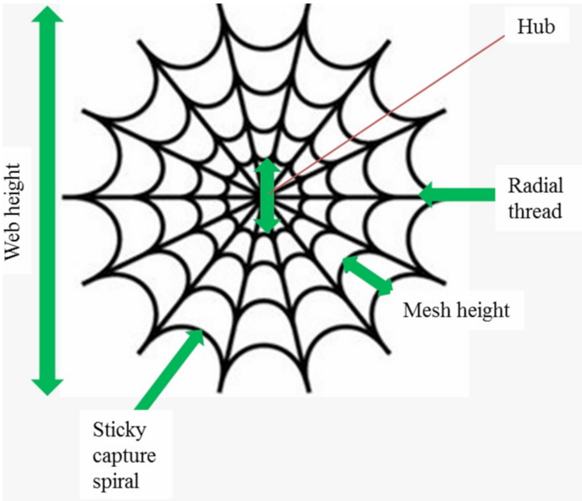


Figure 2.1. An illustration of mesh is a spider's web.

Source: https://www.pngkit.com/view/u2q8u2y3u2r5t4o0_web-diagram-spiderman-spider-web-clipart/.

In reality, all of this promises a lot of freedom, especially when it comes to launching a new network or expanding an established one. Imagine the chore of connecting five individuals in their home and yard that is becoming progressively frequent.

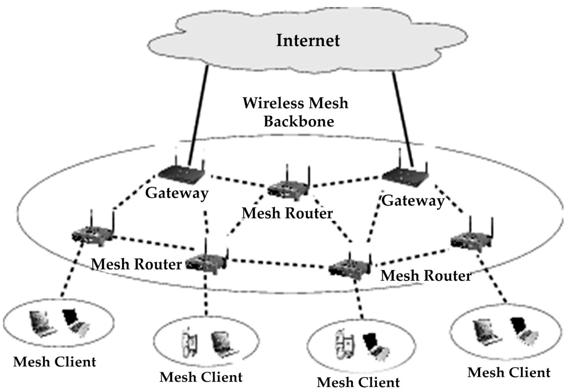


Figure 2.2. A wireless mesh network as an example.

Source: https://www.researchgate.net/figure/An-Example-of-Wireless-Mesh-Network_fig1_220963593.

Let us attempt it using the cellular concept or entry point first, and then the mesh approach second. The example will be kept as simple as possible (Figure 2.2).

Assume that the wireless devices range barely surpasses the house's maximum dimensions. Therefore, the scenario is the same for mesh and cell-based approaches; both may cover the entire house. Let us assume someone walks towards the garden far end that is significantly longer than that of the house's size. This is too much for the cell-based system to handle; the radios are just out of range. The mesh-based technology can handle one condition: a third individual walks among the home and the garden's end (Hur et al., 2013). These units can now interact in the same way they did before. This unit at the further end of the yard merely multi-hops, relaying it through the third person's unit. Multi-hopping may handle length, and therefore we should remember that this implies that it could also handle clutter by hopping over obstacles (Wang et al., 2009).

2.3. MESH'S FUTURE ROLE IN NETWORKS

It is important to put mesh networks in the context of a larger communications ecosystem to capture their full potential. Like many others in this sector, we anticipate that in the future, this will most probably comprise a diverse set of wireless communications coupled to a common central network relying on IP packet switching (Darroudi and Gomez, 2017).

As a result, we envision the future as a gradual merger of the WLAN and cellular approaches, as shown in Figure 2.3, with specialized protocols and interfaces substantially gone.

This is frequently described as 'B3G' in the literature, which stands for 'beyond 3G.' Existing cellular focus groups generally use such words; however, WLAN groups get a similar goal-possibly it could be dubbed "beyond Wi-Fi." As a result, BWi-Fi, and B3G are the similar integrated vision, and thus it must be postponed or perhaps eliminated the requirement for a brand-new, customize 4G network (Waharte et al., 2006).

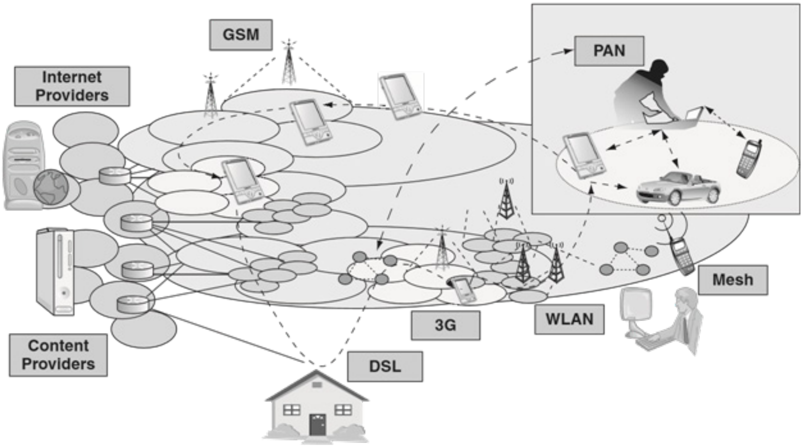


Figure 2.3. Utilizing an IP core, next mobile integrative vision will be possible.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/fundamentals-of-mesh-technology/99A46079C269EA90BD64952 4B9ED17BF.

To put it another way, we believe 4G will resemble Figure 2.3. In addition to 3G and WLAN, meshes are intended to give a supplementary access path further into the center. To put it another way, the mesh would be a supplement to existing access technologies instead of a substitute. While the above may appear self-evident, some have argued that mesh is much greater of a unilateral revolution than an evolutionary component (Guo et al., 2014).

- It is important considering a few of the common forms of networks that are being utilized to connect to the network's core. Users are connected to the Internet via service providers (ISPs) of the Internet through the core. In certain future economic models, content producers may be especially tightly connected with ISPs. The core allows access at a wide range of data rates from such a variety of devices, that is a suitable fit for TCP/granularity IP's of service. The following are some examples of technologies (Camp et al., 2008).
- PAN is an acronym for personal area networks (PANs). This might, for example, make use of Bluetooth and have a mesh-like architecture. The present speed is less than 1 megabit per second

(however, 100 megabits per second is expected), and the range is limited to 10 meters. It is necessary to have access points.

- GSM/3G — cellular phones of the second generation and third. Rates of data will be lower than 2 Mbps at first, having an average of many hundred kbps.
- This range is extensive, spanning many kilometers. It is based on a base station infrastructure that has been deployed.
- Digital subscriber line (DSL) will most likely be a connection of point-to-point with ATM or Ethernet packets carried through fixed pairs of copper. Based on network load and distance, the speed is presently about 8 Mbps (contention) (Akyildiz et al., 2005).
- WLAN is an acronym for wireless local area network. This can give the quickest access to the core; a speed of 54 Mbps is possible, although 11 Mbps being common today. It has a range of about 100 meters. Various WLANs provide users the option of employing peer-to-peer networking or infrastructure, although the vast majority rely on access point infrastructure.
- Mesh-used sparingly in the earlier adopter market at the moment. This book is going to look into its performance abilities. It has the potential to be high-speed, having excellent coverage and no infrastructure requirements (Sentinelli et al., 2007).

2.4. WHAT ARE MESHES AND HOW DO THEY WORK?

As we go into the details of mesh, it is important to first define what a mesh network is. The technique and nomenclature for mesh networking are discussed in this section. It goes on to define the words ad hoc and mesh in more detail (Marina et al., 2010).

2.4.1. Mesh Types

There are three fundamental mesh type designs, for that we will refer through this book's talks. The three kinds are discussed in this section (Hiertz et al., 2010):

- **Pure Mesh:** With a pure mesh, all traffic is intra-mesh, meaning the mesh is separated. All traffic is routed through a single sort of node, the consumer node.

- **Hybrid Mesh:** A pure mesh having a node sorts of hierarchy, with backbone pathways introduced to boost performance. In another terms, there is indeed a second network that sits on top of the mesh and handles just long-distance data. A hierarchy of route layers can be established in wireless meshes by simply adding more specialized bands, or radio channels.
- **Access Mesh:** A mesh having a node kinds of hierarchy, as described above, but with significant extra-mesh traffic. To put it another way, the overlaid routing network includes gateways to many other networks, like the Internet (Figure 2.4).

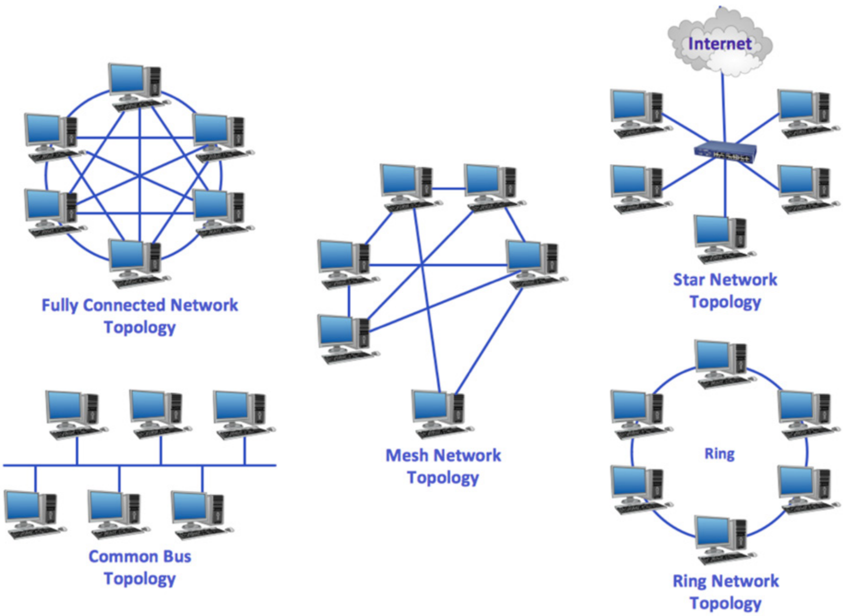


Figure 2.4. Network topologies in a variety of types.

Source: https://www.swissns.ch/site/2017/06/the-various-types-of-network-topologies/.

We will find subsequently that either the material to be accessed is within or outside the mesh affects traffic flow or, as a result, the best mesh architecture. In other terms, the kind of mesh needed in a given circumstance is determined by the customer's and application's requirements. It is important to mention right away that much of the earlier publicized research was financed by the army and focused on pure meshes that do not necessarily transition effectively to public telecommunications needs that typically need an accessible mesh (Baker, 2005).

2.4.2. Ad Hoc versus Planned

The network's design reasoning is the subject of a second differentiation. A designed network, like a cellular network, has a maximum number of consumers and guarded cells where it can function. The advantage of this is that intervention is minimized, and as a result, assurances of service delivery quality may be provided. The disadvantage is that infrastructure is required; in other terms, the operator first must establish provisions for each location where service is required (Zhao and Jain, 2011).

Ad hoc connections are possible in an unplanned network. The term ad hoc means literally "for this purpose," implying a temporary setup that may be used as needed. Its advantage would be that no infrastructure is required, and customers can expand the coverage area themselves-however, as we will see later, this must entail an efficiency trade-off, if everything else is equal. Its disadvantage is that without preparation, there is no way to limit the impact of other consumers' intervention. As a result, because the efficiency of an application is outside the authority of any single party, there can be no definitive assurances about the reliability of the supplied service (Zhao and Jain, 2011).

2.4.3. An Ad Hoc Pristine Mesh Network's Properties

The features of a purified, ad hoc mesh network are summarized in Table 2.1. These are all the qualities that will be discussed in more detail in subsequent chapters.

2.4.4. Properties of an Access Mesh

A hybrid mesh, that is the next level of complexity, is identical to the sort of mesh mentioned in Table 2.1, excepting that certain nodes will have their network connections, able to link to an internal backbone routing. Adding the ability for certain nodes to act as the gateway to outer networks will be a reasonable next step. Naturally, this is precisely the setup that is required to offer Internet service to several customers. As a result, the mesh form is referred to as an access mesh. Over the entire book, the access mesh is the foremost significant mesh form (Amaldi et al., 2008).

2.4.5. Multi-Hopping versus Meshing

Multi-hopping was previously used to enhance coverage by raising hopping or distance around barriers in a fundamental sample of wireless communications at home. The distinction between multi-hopping and meshing is therefore raised (Karrer et al., 2004).

Table 2.1. An ad hoc mesh networks characteristics (Alotaibi and Mukherjee, 2004)

No Separate Infrastructure	In within mesh, all activity is given and performed. This covers power management, security, routing, management, and invoicing, etc. Here is no central counterpart to a cellular network's base station or protection and authenticating center. (This is not the case with an access mesh; shown below).
Ad Hoc	Unscheduled. As a result, interruption, and coverage are unregulated, and that is the polar opposite of a normal cellular situation. It directly raises concerns about service quality.
Wireless	Wireless functioning is necessary to eliminate infrastructure or facilitate mobility. This might refer to optical or radio technology, although this book focuses on radio. The quality of radio links is less than that of wired lines; packet loss over radio is considered normal, while failure on wired connections is considered congestion. When employed over radio networks, transport protocols (as defined for wired networks) might have had the 'wrong' response.
Mobility	Nodes have complete freedom to move and even vanish. As a result, network linkages may be quite dynamic.
Routing	Every node will be obliged to follow a routing protocol. It may be done both proactively, by keeping tables updated, or reactively, by building routes as needed. Routing generates overhead that varies depending on the protocol, traffic, and node mobility.
Relay	It is possible that all nodes will be obliged to communicate information to other nodes. The bandwidth accessible to every node consumer will be reduced as a result.

Inhomogeneity	Beyond the subset abilities required for fundamental mesh functioning, hardly all nodes must be similar. Other network connections (outside links in the access mesh scenario, shown below) may exist on certain nodes.
Multi-Hop	Multi-hop, which is a consequence of routing and relay, is a coverage enhancer, particularly in a crowded atmosphere.

In reality, the words are not always clearly stated, so the mesh is frequently used in a general sense. Throughout this book, we shall consider the distinction as follows when it counts. Multi-hopping including active route variety may be summed up as meshing. A network of multi-hop may be compared to nodes in a branch and tree structure, whilst a mesh can be compared to nodes in a web of spiders. In other words, a particular traffic flow in a mesh network may be divided among two or even more routes to the target, but in a network of multi-hop, there is only one routing at any one moment. Despite this, the network of multi-hop maintains the capacity to navigate past barriers. This crucial characteristic of hopping over obstacles will be mentioned several times throughout this book, and it is arguably the most persistent advantage provided by both multi-hop and mesh networks (Bhagwat et al., 2004; Vaidya et al., 2013).

2.5. BASIC OF MESH TECHNOLOGY

Study every layer of a general communications protocol architecture in sequence, as seen in Figure 2.5, to cover the basics.

The physical layer (PHY) is at the stack bottom. This category includes components that directly affect the air interface, such as transceiver circuits and antennas. By implication, this covers specific design factors like transmit power and modulation scheme selection (Jinkang et al., 2020).

The mechanism through which accessibility towards the air interface is decided, on the other hand, is the responsibility of the medium access control (MAC) layer, or just MAC. As an example, techniques that allow many consumers to utilize the medium in a greater or fewer equitable manner, like the randomized collision prevention procedures utilized in 802.11 or the organized frequency and time division multiplexing utilized in GSM, will fall under this category (Lee et al., 2006).

Some form of addressing system is necessary to allow nodes to discover and interact with one another; this is provided in the routing layer. The

Internet protocol, for example, is becoming widely used. It is so successful that the most recent iteration, IPv6, offers significantly more addressing capacity in reaction to a global requirement that any possible device may require an IP address. Although IP is the system of addressing, a routing protocol is also required. It was routing information protocol (RIP) on earlier Internet routers. Though RIP is continuously in use, as the Internet has developed, it has been supplemented with more complicated routing protocols. However, in comparison to the fixed Internet, a routing system for a mesh that is mobile may have to work incredibly hard, necessitating alternative solutions, as we will discover (Iskandar et al., 2019).

The transport layer is the next tier in the stack, and it is accountable for organizing how data packets are transmitted through the link and also what, if something happens if packets do not reach at their target.

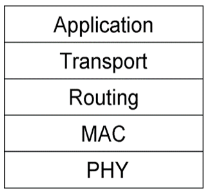


Figure 2.5. A protocol stack that is general in nature.

Source: https://www.net.t-labs.tu-berlin.de/teaching/computer_networking/01.07.htm.

TCP is a mechanism of packet delivery verification and combines a congestion management system is the most well-known example of this. TCP/IP is projected to become a standard in communications systems for both addressing and transport. Throughout the book, we will presuppose the TCP/IP stack, but that does not imply we have to presuppose standard protocols of Internet routing like RIP and others (Bohr and Beck-Broichsitter, 2015).

Lastly, the layer of application, in our simplistic architecture, encompasses almost anything up to a consumer interface including a screen and keyboard. In many other terms, it allows the node consumer to execute any work they want. We are not concerned in the fine details of the application layer in general; instead, we are concerned in how the apps and transport protocol interact. As a result, we will look at applications and transportation together (Marescotti et al., 2020).

To put it all altogether, an 802.11 ad hoc MAC carrying TCP/IP and an 802.11 radio (PHY) to permit the transfer of email data of an application is an example stack.

The chapter starts just at the PHY by examining the two methods for creating a mesh. Further it starts to build, through a series of illustrations, how well a pure mesh design may be evolved into an accessible mesh architecture. This is informed by the evaluation of the predicted traffic flows application. When evaluating the MAC, different techniques are offered, emphasizing that a MAC needing centralized coordination is probably to be ideally suited to that of an ad hoc network. Its mobility features of a mesh are essential when analyzing routing. This instantly separates routing protocol techniques into two groups. Lastly, we discuss the characteristics of applications, for instance, non-real-time, real-time, especially as they link to transport protocols (Iskandar et al., 2018; Stevenson et al., 2019).

2.5.1. Physical Layer (PHY)

A most key question is how meshes are formed. In actuality, there are two ways to go about it.

2.5.1.1. Logical versus Physical Meshes

Logically or physically, a mesh can be created. The difference is significant from the standpoint of interference footprints, which vary in the two instances.

Physical-meshes are those that are controlled by physical-level constraints, for instance, a design constraint like signal path constraint/directional antennas triggered by medium or terrain. The wireless Internet, for instance, is an absolute physical-mesh in that broadcasting on one connection does not tamper with other links. While, a logical mesh, is designed above the PHY, with no physical constraints enforced by the environment or system a network's neighbors. In an open-area, omnidirectional antennas might be linked as a logical-mesh; certainly, this is accomplished at the MAC threshold because it is not possible at the PHY level (Knupp, 1999).

The logical and physical meshes are depicted in both Figures 2.6 and 2.7, respectively. Though the links are bi-directional, Figure 2.6 depicts antenna-pointing guidelines.

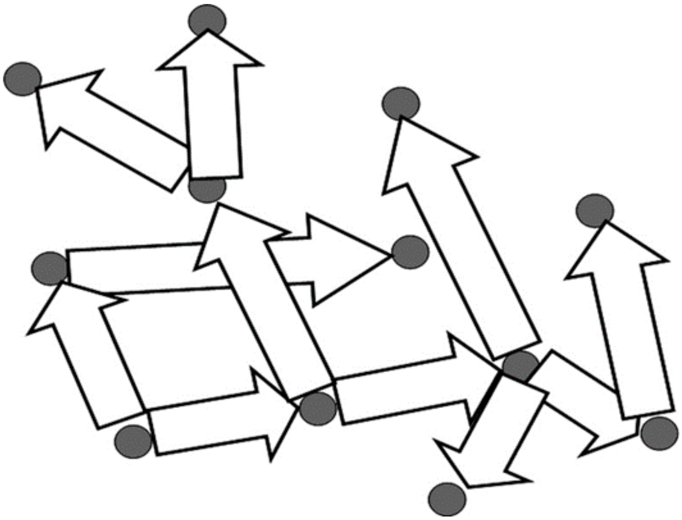


Figure 2.6. A mesh created physically.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/fundamentals-of-mesh-technology/99A46079C269EA90BD649524B9ED17BF.

Various applications of interest are possible to attain with logical-mesh and omnidirectional antennas. This is particularly important in the most intriguing and latest mesh networking sector, wireless sensor networks (WSNs), and vehicular ad-hoc networks (VANETs) (Barnett et al., 1996).

2.5.1.2. Extra-Mesh and Intra-Mesh Traffic Flows

Meshes were originally created by the military to deal with problems where there were no facilities. No junction could be more essential to another than it had to be, or the system's operation would be jeopardized. As a result, the idea of a server or centralized controller was rarely used. However, our mesh applications are not like this; the application and traffic are diverse, particularly if our goal is to connect with the Internet, however, we do want to keep the ad-hoc element (Hugo and Bayer, 2011).

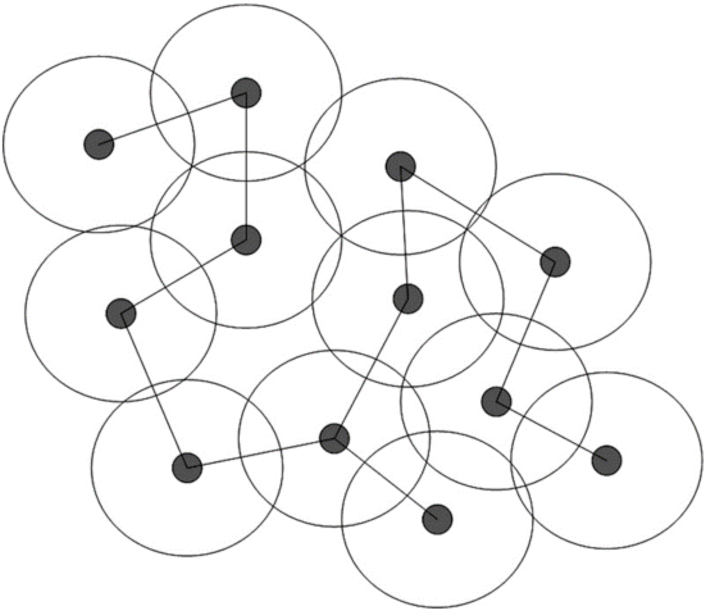


Figure 2.7. A mesh created logically.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/fundamentals-of-mesh-technology/99A46079C269EA90BD649524B9ED17BF.

Traffic flows differ depending on whether the subject matter to be ingress is inside or outside the mesh network, so applicant network-architecture for mesh networks is based on that. As a result, there are two primary traffic flows intra-mesh and extra-mesh. Certainly, these are not mutually exclusive; in practice, a real application will most likely combine the two (Bruno and Nurchis, 2010).

Let us start with applications that do not require ingress to external/central resources, such as team communication. For these applications, traffic flow can be encompassed inside the mesh, with consumers interacting with one another either directly if spectrum allows or through peer-hopping. Intra-mesh traffic is typically restricted to closed user groups in today's marketplaces like (Houaidia et al., 2014):

- Activities that are not reliant on facilities, such as disaster and emergency relief; and
- Local community, intra-company, and file-sharing on-campus, etc.

2.5.2. Traffic Architectures of Intra-Mesh

All traffic sinks and sources are contained inside the mesh network in this scenario, so there is no need to link to an external network, like a control center and the Internet. As shown in Figure 2.8, the mesh for this intra-mesh traffic could be completely made up of follower nodes. Traffic assembly will only take place in this situation where consumers are focused, especially near retail centers, communities, and business centers (Lim et al., 2014).

As a result, the network's coverage and integrity can be improved by adding specified nodes to help with local traffic assembly, as shown in Figure 2.9. The specified nodes are not substitutes for current nodes, but rather new additions.

This fixed-node may be included for a variety of purposes (Thaalbi and Tabbane, 2012):

- To maintain a minimum level of connectivity and coverage regardless of client concentration. This may be necessary, for instance, to resolve a fluctuating shortage of follower nodes that occurs as consumers out of a city and commute in.

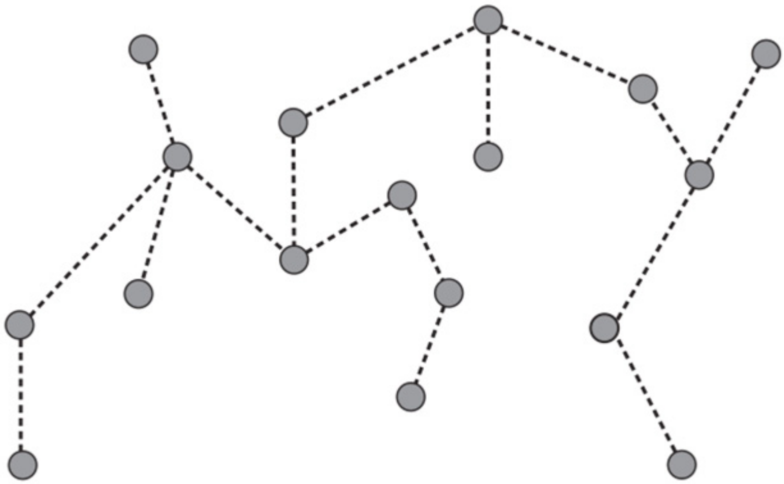


Figure 2.8. Route connections formed by user nodes.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/0DE3EF74BA5FEE59999B18001B4293B0.

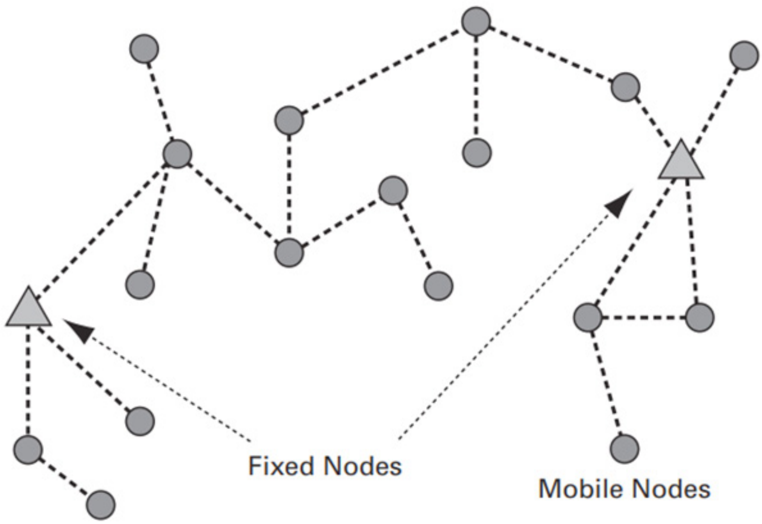


Figure 2.9. Within a network, addition of permanent relay nodes.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/fundamentals-of-mesh-technology/99A46079C269EA90BD649524B9ED17BF.

- When consumer nodes are thinly distributed, to improve coverage and connectivity. This may be the scenario through the early stages of the service's roll-out when client numbers are insufficient to ensure mesh accessibility. They are commonly referred to as-seed nodes-in this sense.
- To improve coverage by assisting routing around constraints, like those found in urban areas.
- To increase throughput in densely populated areas.

Let us take it a step forward and consider end-to-end traffic that travels over longer paths and involves a large number of hops. A pyramid of specified relay-node, each with an extended communication range, could be put into place to help with this. Inside the mesh, this creates a backbone network, as shown in Figure 2.10. It is possible to have a wired backbone. This architectural design excludes the potential loss of efficiency and increase in end-to-end lag that comes with a large number of hops (Flickenger et al., 2007; Yang et al., 2009).

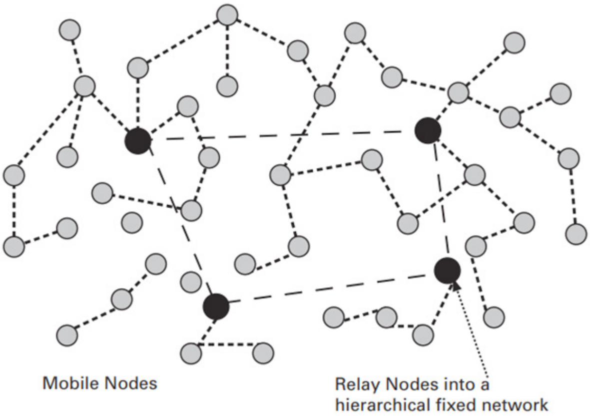


Figure 2.10. Mesh connected to a backbone network.

Source: https://www.amazon.com/Essentials-Wireless-Mesh-Networking-Cambridge/dp/052187680X.

The back-bone architectural design would have to use routing, with the planned route being determined by the present state of each possible connection in aspects of some figure of merit, such as delay, throughput, and so on.

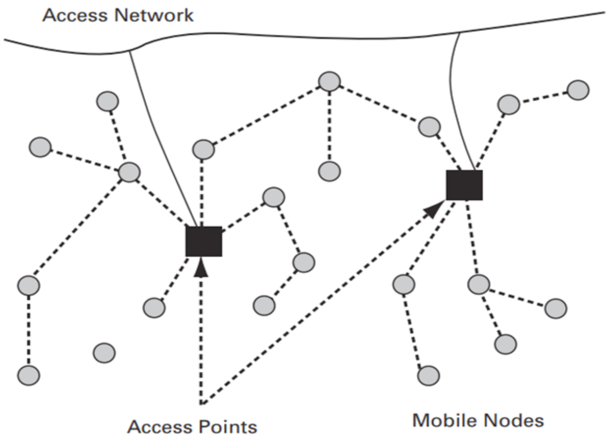


Figure 2.11. The 'access mesh' is an extra-mesh traffic flow that is routed through access points.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/0DE3EF74BA5FEE59999B18001B4293B0.

A few industrial mesh solutions use independent and dedicated radio stations for one or more tiers of backbone (Figure 2.11) (Shioda and Komatsu, 2010).

2.5.3. Traffic Flow of Extra-Mesh

Now we will look at the additional mesh traffic flow, which is the second category of traffic flow. In this scenario, traffic enters and exits the mesh through one or even more-access points-linked to a private and public ingress network (Wu et al., 2011).

The traffic flow is no matter how long distributed equally throughout mobile-node, as it is in the backhaul mesh network, and yet is centered on nodes near the access point. When it comes to achieving adequate service quality, this has significant ramifications when it comes to the accessibility and attitude of customer nodes in the proximity of the access point. The existence of an access point, on the other hand, has a good impact on service quality and mesh scalability, as will be discussed later in the book (Deng et al., 2016).

In conclusion, we require an access-mesh architectural design for Internet connectivity, and the traffic density implications that this entails are a repercussion that we must address.

2.5.4. Medium Access Regulation

To enable a consumer to access the physical medium-which in our scenario is the air interface-medium access strategies are essential. As a result, the MAC strategy is chosen and its associated performance must be a determining factor of system performance. One might suppose that in an idealistic world, each node's connection to the route would be fairly adjudicated (Livingstone, 2007). This is true in some instances. When things go wrong, one of the most common causes is that the MAC function was not or could not be consolidated. Instead of relying on centralization, each node can take part in a MAC function that is shared among all-node (Bollinger, 1976).

2.5.4.1. MACs for Planned and Fixed Applications

Where nodes are repaired and thus recognized by a central controller, a highly centralized MAC is more adequate. This information helps the use of a completely mechanistic MAC protocol. Deterministic protocols are usually 'slotted,' which means the MAC will give the node a chunk of spreading code, frequency, time, and other distinctive resource allocation where it can transfer. The MAC instances just given are known as CDMA-code-division multiple-access, frequency, and time-, FDMA, and TDMA, respectively (Borgonovo et al., 2004).

2.5.4.2. MACs for Ad Hoc and Mobile Applications

Where node position is not secured, a decentralized MAC is more relevant. Each-node in a decentralized MAC takes part in the MAC procedure. It makes no difference if a node vanishes due to simply and mobility because it is turned out by the consumer in this manner. Random-access or, less commonly, controlled access to the route can be used to continue operating decentralized MACs. There are not many instances of controlled-access, decentralized MACs in the mainstream, and yet IEEE 802.16e, which gives traffic-flow responsibilities at the MAC level, is one (Yaqoob et al., 2016).

The random availability distributed MAC, like the CSMA/CA (collision avoidance) of 802.11, is much more prevalent and appropriate to mesh, in which collisions are (mainly) managed to avoid by something like a listen-before-talk setup controlled by the nodes itself, instead of any task of preferences or other tries at global international cooperation. Collisions can still happen in some cases, and the approach is always slower than a non-random, determinism access technique. The relative ease with which it can be implemented is a significant draw. 802.11 is the best example, as previously said (Winters, 2006).

2.5.5. Routing

First and foremost, let us define routing: it is the function of determining which way to follow to transfer data from one to the end. It has to have an addressing system and a routing protocol. To put it another way, if the addressing system consisted just of residential addresses, the routing protocol would be a smart postman (Godfrey et al., 2009).

In a mesh, routing methods are put to the test, especially if the mesh is mobile. Consider our postman's job if homes routinely vanished and returned elsewhere, and when they all traveled in various directions all the time. That is the essence of the problem with the mobile routing protocol. Routing protocols have to be effective, and that they must either maintain their information up to date proactively or respond fast when new routes are needed. Which of the above two routing techniques is preferable relies on mesh user behavior (e.g., the number of hand-overs required) and the content that must be transported (e.g., video vs. basic file transfer)? Every mesh node is required to engage in the relay and routing of other mesh nodes' traffic, which we will discuss next (Laporte and Osman, 1995).

2.5.5.1. Every Node Like a Router

Every node in an ad hoc network participates in the network not just as a probable sink and source of traffic, however, also as a router and relay, allowing traffic to be sent among nodes within the network. As a result, in an ad hoc mesh, every node must know the route traffic must take in an attempt to reach its target. This is quite similar to how routers behave on the Internet, with the exception that not even all Internet nodes must be routers, and in fact, not all are. Mobility, as previously stated, adds instability to the routing issue (Kumar et al., 1998).

2.5.5.2. Every Node Like a Relay

It is required for nodes to serve as relays to build a mesh. This is necessary, but it has some implications. To begin, by functioning as a relay, a node bears an additional workload beyond that required to fulfill its customers' needs. Nodes frequently require to be capable to transmit traffic of a quantity many times more of their operation, i.e., it should manage not just their user-produced traffic but probably that of multiple additional users, as per commercial and academic published work. Meshes, on the other hand, will necessitate more competent user nodes than cellular systems (Tang et al., 2006).

Second, establishing a service level that is dependent on the efficiency of user nodes makes upgrading and maintenance more challenging. When EDGE was first introduced to GSM, for example, it was feasible to update base stations and then enable subscribers to join up for the new features as and when they were needed, if it is at all. Consumers in a mesh system rely on the established base of other subscribers, thus additional services cannot be offered even if all or a significant portion of current subscribers are convinced to update their devices (Han et al., 2009).

2.5.5.3. Reactive Routing and Proactive in Ad Hoc Networks

Protocols for ad hoc routing are employed in situations in which there is a universal routing strategy but not essentially a well-regulated infrastructure network. In ad hoc routing, there are two types of protocols: reactive and proactive. The 'ordinary' routing protocols utilized in wired networks, like today's Internet, form the foundation for proactive routing protocols. Link state or distance vector algorithms are prevalent. When choosing the optimum route, the distance vector generally considers the hops number as a metric to reduce, but it may also examine other characteristics such as network latency and bandwidth. It is utilized to build a routing table that is shared by all routers. Link state processing is more complicated, requiring every router to create a separate network map (Tyagi and Chauhan, 2010).

As a result, proactive protocols seek to create a portrait of routes inside the network locally, at every node, before they are needed for usage. Routing tables are generally created regularly as part of the protocol's routine functioning of exchanging routing update packets. In a typical operation, it has the benefit of pre-compiling the routes, allowing packet forwarding to occur as fast as a packet for a certain target arrives at a node. The disadvantage would be that routes may well be computed and recalculated even when they are not needed for data. This consumes bandwidth and, in the case of mobile nodes, battery power by receiving and sending redundant routing information (Shivahare et al., 2012).

2.5.6. Applications and Transport

We combine these since it would be pointless to discuss a transport protocol before first understanding what would be carried. For example, big packets might be the most effective way to send a huge database file. If the huge file, on the other hand, was a genuine video stream, utilizing tiny packets might make better sense. It is since if a genuine video packet is lost, it is typically disregarded. Re-transmitting the packet is pointless because time has passed, and it is much more desirable to the consumer to drop the packet completely. Dropping a huge packet is more damaging than dropping a tiny packet. This shows two aspects of transport protocols: re-transmission policy and packet size (LeFloch and Mercier, 2020).

Transport protocols, on the other hand, are unlikely to be rebuilt just to support mesh networks or another innovative network. Inside the Internet, TCP, IP, and stream protocols like formats for a real-time streaming protocol (RTSP) and commercial streaming are well-established. After all, the purpose of a tiered communications stack would be that upper layers may be separated from the bottom layer (Yamartino, 1993).

REFERENCES

1. Ahmed, R., & Aslani, P., (2014). What is patient adherence? A terminology overview. *International Journal of Clinical Pharmacy*, *36*(1), 4–7.
2. Akyildiz, I. F., Wang, X., & Wang, W., (2005). Wireless mesh networks: A survey. *Computer Networks*, *47*(4), 445–487.
3. Ali, A., Ahmed, M. E., Piran, M., & Suh, D. Y., (2014). Resource optimization scheme for multimedia-enabled wireless mesh networks. *Sensors*, *14*(8), 14500–14525.
4. Alotaibi, E., & Mukherjee, B., (2012). A survey on routing algorithms for wireless ad-hoc and mesh networks. *Computer Networks*, *56*(2), 940–965.
5. Amaldi, E., Capone, A., Cesana, M., Filippini, I., & Malucelli, F., (2008). Optimization models and methods for planning wireless mesh networks. *Computer Networks*, *52*(11), 2159–2171.
6. Avallone, S., Akyildiz, I. F., & Ventre, G., (2008). A channel and rate assignment algorithm and a layer-2.5 forwarding paradigm for multi-radio wireless mesh networks. *IEEE/ACM Transactions on Networking*, *17*(1), 267–280.
7. Baker, N., (2005). ZigBee and Bluetooth strengths and weaknesses for industrial applications. *Computing & Control Engineering Journal*, *16*(2), 20–25.
8. Barnett, M., Payne, D. G., Van De Geijn, R. A., & Watts, J., (1996). Broadcasting on meshes with wormhole routing. *Journal of Parallel and Distributed Computing*, *35*(2), 111–122.
9. Bhagwat, P., Raman, B., & Sanghi, D., (2004). Turning 802.11 inside-out. *ACM SIGCOMM Computer Communication Review*, *34*(1), 33–38.
10. Bohr, A., & Beck-Broichsitter, M., (2015). Generation of tailored aerosols for inhalative drug delivery employing recent vibrating-mesh nebulizer systems. *Therapeutic Delivery*, *6*(5), 621–636.
11. Bollinger, L. C., (1976). Freedom of the press and public access: Toward a theory of partial regulation of the mass media. *Michigan Law Review*, *75*(1), 1–42.
12. Borgonovo, F., Capone, A., Cesana, M., & Fratta, L., (2004). ADHOC MAC: New MAC architecture for ad hoc networks providing efficient

and reliable point-to-point and broadcast services. *Wireless Networks*, *10*(4), 359–366.

13. Bruno, R., & Nurchis, M., (2010). Survey on diversity-based routing in wireless mesh networks: Challenges and solutions. *Computer Communications*, *33*(3), 269–282.
14. Camp, J. D., & Knightly, E. W., (2008). The IEEE 802.11 s extended service set mesh networking standard. *IEEE Communications Magazine*, *46*(8), 120–126.
15. Chowdhury, K. R., & Akyildiz, I. F., (2008). Cognitive wireless mesh networks with dynamic spectrum access. *IEEE Journal on Selected Areas in Communications*, *26*(1), 168–181.
16. Darroudi, S. M., & Gomez, C., (2017). Bluetooth low energy mesh networks: A survey. *Sensors*, *17*(7), 1467.
17. Deng, X., He, L., Zhu, C., Dong, M., Ota, K., & Cai, L., (2016). QoS-aware and load-balance routing for IEEE 802.11s-based neighborhood area network in smart grid. *Wireless Personal Communications*, *89*(4), 1065–1088.
18. Ding, Y., & Xiao, L., (2011). Channel allocation in multi-channel wireless mesh networks. *Computer Communications*, *34*(7), 803–815.
19. Eckhardt, D. A., & Steenkiste, P., (1999). A trace-based evaluation of adaptive error correction for a wireless local area network. *Mobile Networks and Applications*, *4*(4), 273–287.
20. Flickenger, R., Aichele, C., Büttrich, S., & Drewett, L. M., (2007). *Wireless Networking in the Developing World: A Practical Guide to Planning and Building Low-Cost Telecommunications Infrastructure*, *9*, 2009.
21. Geraldi, N. R., Dodd, L. E., Xu, B. B., Wells, G. G., Wood, D., Newton, M. I., & McHale, G., (2017). Drag reduction properties of superhydrophobic mesh pipes. *Surface Topography: Metrology and Properties*, *5*(3), 034001.
22. Godfrey, P. B., Ganichev, I., Shenker, S., & Stoica, I., (2009). Pathlet routing. *ACM SIGCOMM Computer Communication Review*, *39*(4), 111–122.
23. Goldschlag, D., Reed, M., & Syverson, P., (1999). Onion routing. *Communications of the ACM*, *42*(2), 39–41.

24. Guo, P., Wang, J., Geng, X. H., Kim, C. S., & Kim, J. U., (2014). A variable threshold-value authentication architecture for wireless mesh networks. *Journal of Internet Technology*, *15*(6), 929–935.
25. Han, X., Cao, X., Lloyd, E. L., & Shen, C. C., (2009). Fault-tolerant relay node placement in heterogeneous wireless sensor networks. *IEEE Transactions on Mobile Computing*, *9*(5), 643–656.
26. Hiertz, G. R., Denteneer, D., Max, S., Taori, R., Cardona, J., Berlemann, L., & Walke, B., (2010). IEEE 802.11s: The WLAN mesh standard. *IEEE Wireless Communications*, *17*(1), 104–111.
27. Hou, Y. T., Shi, Y., & Sherali, H. D., (2008). Spectrum sharing for multi-hop networking with cognitive radios. *IEEE Journal on Selected Areas in Communications*, *26*(1), 146–155.
28. Houaidia, C., Idoudi, H., Van Den Bossche, A., Val, T., & Saidane, L. A., (2014). Towards an optimized traffic-aware routing in wireless mesh networks. *International Journal of Space-Based and Situated Computing*, *4*(3–4), 217–232.
29. Hur, S., Kim, T., Love, D. J., Krogmeier, J. V., Thomas, T. A., & Ghosh, A., (2013). Millimeter wave beamforming for wireless backhaul and access in small cell networks. *IEEE Transactions on Communications*, *61*(10), 4391–4403.
30. Iskandar, A. R., Martin, F., Leroy, P., Schlage, W. K., Mathis, C., Titz, B., & Hoeng, J., (2018). Comparative biological impacts of an aerosol from carbon-heated tobacco and smoke from cigarettes on human respiratory epithelial cultures: A systems toxicology assessment. *Food and Chemical Toxicology*, *115*, 109–126.
31. Iskandar, A. R., Zanetti, F., Marescotti, D., Titz, B., Sewer, A., Kondylis, A., & Hoeng, J., (2019). Application of a multi-layer systems toxicology framework for in vitro assessment of the biological effects of classic tobacco e-liquid and its corresponding aerosol using an e-cigarette device with MESH™ technology. *Archives of Toxicology*, *93*(11), 3229–3247.
32. Jinkang, Z. H. U., (2020). Wireless mesh technology and network. *ZTE Communications*, *6*(2), 1–6.
33. Jun, J., & Sichitiu, M. L., (2003). The nominal capacity of wireless mesh networks. *IEEE Wireless Communications*, *10*(5), 8–14.
34. Karrer, R., Sabharwal, A., & Knightly, E., (2004). Enabling large-scale wireless broadband: The case for TAPs. *ACM SIGCOMM Computer Communication Review*, *34*(1), 27–32.

35. Knupp, P. M., (1999). Winslow smoothing on two-dimensional unstructured meshes. *Engineering with Computers*, *15*(3), 263–268.
36. Komenda, M., Schwarz, D., Švancara, J., Vaitsis, C., Zary, N., & Dušek, L., (2015). Practical use of medical terminology in curriculum mapping. *Computers in Biology and Medicine*, *63*, 74–82.
37. Kumar, V. P., Lakshman, T. V., & Stiliadis, D., (1998). Beyond best effort: Router architectures for the differentiated services of tomorrow's internet. *IEEE Communications Magazine*, *36*(5), 152–164.
38. Laporte, G., & Osman, I. H., (1995). Routing problems: A bibliography. *Annals of Operations Research*, *61*(1), 227–262.
39. Lee, M. J., Zheng, J., Ko, Y. B., & Shrestha, D. M., (2006). Emerging standards for wireless mesh technology. *IEEE Wireless Communications*, *13*(2), 56–63.
40. LeFloch, P. G., & Mercier, J. M., (2020). The transport-based mesh-free method: A short review. *Wilmott*, *2020*(109), 52–57.
41. Lim, A. O., Wang, X., Kado, Y., & Zhang, B., (2008). A hybrid centralized routing protocol for 802.11 s WMNs. *Mobile Networks and Applications*, *13*(1), 117–131.
42. Livingstone, S., (2007). Strategies of parental regulation in the media-rich home. *Computers in Human Behavior*, *23*(2), 920–941.
43. Marescotti, D., Mathis, C., Belcastro, V., Leroy, P., Acali, S., Martin, F., & Hoeng, J., (2020). Systems toxicology assessment of a representative e-liquid formulation using human primary bronchial epithelial cells. *Toxicology Reports*, *7*, 67–80.
44. Marina, M. K., Das, S. R., & Subramanian, A. P., (2010). A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks. *Computer Networks*, *54*(2), 241–256.
45. Mohsenian-Rad, A. H., & Wong, V. W., (2007). Joint logical topology design, interface assignment, channel allocation, and routing for multi-channel wireless mesh networks. *IEEE Transactions on Wireless Communications*, *6*(12), 4432–4440.
46. Muhendra, R., Rinaldi, A., & Budiman, M., (2017). Development of Wi-Fi mesh infrastructure for internet of things applications. *Procedia Engineering*, *170*, 332–337.
47. Pahlavan, K., & Levesque, A. H., (1994). Wireless data communications. *Proceedings of the IEEE*, *82*(9), 1398–1430.

48. Pandey, S., & Ganz, A., (2006). Design and evaluation of multichannel multirate wireless networks. *Mobile Networks and Applications*, *11*(5), 697–709.
49. Rad, A. H. M., & Wong, V. W., (2008). Cross-layer fair bandwidth sharing for multi-channel wireless mesh networks. *IEEE Transactions on Wireless Communications*, *7*(9), 3436–3445.
50. Raniwala, A., Gopalan, K., & Chiueh, T. C., (2004). Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, *8*(2), 50–65.
51. Sentinelli, A., Marfia, G., Gerla, M., Kleinrock, L., & Tewari, S., (2007). Will IPTV ride the peer-to-peer stream? [peer-to-peer multimedia streaming]. *IEEE Communications Magazine*, *45*(6), 86–92.
52. Shioda, S., & Komatsu, M., (2010). Queueing-model-based analysis for IEEE802. 11 Wireless LANs with non-saturated nodes. *Radio Communications*, *441*, 6–18.
53. Shivahare, B. D., Wahi, C., & Shivhare, S., (2012). Comparison of proactive and reactive routing protocols in mobile ad hoc network using routing protocol property. *International Journal of Emerging Technology and Advanced Engineering*, *2*(3), 356–359.
54. Si, W., Selvakennedy, S., & Zomaya, A. Y., (2010). An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks. *Journal of Parallel and Distributed Computing*, *70*(5), 505–524.
55. Stevenson, M., Czekala, L., Simms, L., Tschierske, N., Larne, O., & Walele, T., (2019). The use of genomic allergen rapid detection (GARD) assays to predict the respiratory and skin sensitizing potential of e-liquids. *Regulatory Toxicology and Pharmacology*, *103*, 158–165.
56. Tang, J., Hao, B., & Sen, A., (2006). Relay node placement in large scale wireless sensor networks. *Computer Communications*, *29*(4), 490–501.
57. Thaalbi, M., & Tabbane, N., (2012). An enhanced geographical routing protocol for wireless mesh networks, 802.11s. *International Journal of Computer Applications*, *51*(10), 4–9.
58. Tyagi, S. S., & Chauhan, R. K., (2010). Performance analysis of proactive and reactive routing protocols for ad hoc networks. *International Journal of Computer Applications*, *1*(14), 27–30.

59. Vaidya, B., Makrakis, D., & Mouftah, H., (2013). Secure and robust multipath routings for advanced metering infrastructure. *The Journal of Supercomputing*, *66*(2), 1071–1092.
60. van Zanten, F., van Iersel, J. J., Paulides, T. J., Verheijen, P. M., Broeders, I. A., Consten, E. C., & Koops, S. E. S., (2019). Long-term mesh erosion rate following abdominal robotic reconstructive pelvic floor surgery: A prospective study and overview of the literature. *International Urogynecology Journal*, *3*(1), 1–11.
61. von Hugo, D., & Bayer, N., (2011). Challenges for wireless mesh networks to provide reliable carrier-grade services. *Advances in Radio Science*, *9*, 377–382.
62. Waharte, S., Boutaba, R., Iraqi, Y., & Ishibashi, B., (2006). Routing protocols in wireless mesh networks: Challenges and design considerations. *Multimedia Tools and Applications*, *29*(3), 285–303.
63. Wang, J., Lan, Z., Pyo, C. W., Baykas, T., Sum, C. S., Rahman, M. A., & Kato, S., (2009). Beam codebook-based beamforming protocol for multi-Gbps millimeter-wave WPAN systems. *IEEE Journal on Selected Areas in Communications*, *27*(8), 1390–1399.
64. Winters, J. H., (2006). Smart antenna techniques and their application to wireless ad hoc networks. *IEEE Wireless Communications*, *13*(4), 77–83.
65. Wu, D., Gupta, D., & Mohapatra, P., (2011). QuRiNet: A wide-area wireless mesh testbed for research and experimental evaluations. *Ad Hoc Networks*, *9*(7), 1221–1237.
66. Wu, T. H., (1994). A passive protected self-healing mesh network architecture and applications. *IEEE/ACM Transactions on Networking*, *2*(1), 40–52.
67. Xie, J., & Wang, X., (2008). A survey of mobility management in hybrid wireless mesh networks. *IEEE Network*, *22*(6), 34–40.
68. Yamartino, R. J., (1993). Nonnegative, conserved scalar transport using grid-cell-centered, spectrally constrained Blackman Cubics for applications on a variable-thickness mesh. *Monthly Weather Review*, *121*(3), 753–763.
69. Yang, G. Y., Chen, L., Jiang, P., Guo, Z. Y., Wang, W., & Liu, Z. P., (2016). Fabrication of tunable 3D graphene mesh network with enhanced electrical and thermal properties for high-rate aluminum-ion battery application. *RSC Advances*, *6*(53), 47655–47660.

70. Yang, K., Ma, J. F., & Miao, Z. H., (2009). Hybrid routing protocol for wireless mesh network. In: *2009 International Conference on Computational Intelligence and Security* (Vol. 1, pp. 547–551).
71. Yaqoob, I., Ahmed, E., Gani, A., Mokhtar, S., Imran, M., & Guizani, S., (2016). Mobile ad hoc cloud: A survey. *Wireless Communications and Mobile Computing*, *16*(16), 2572–2589.
72. Zhang, J., & Mukheriee, B., (2004). A review of fault management in WDM mesh networks: Basic concepts and research challenges. *IEEE Network*, *18*(2), 41–48.
73. Zhang, Y., & Fang, Y., (2006). ARSA: An attack-resilient security architecture for multihop wireless mesh networks. *IEEE Journal on Selected Areas in Communications*, *24*(10), 1916–1928.
74. Zhao, S., & Jain, S., (2011). Ad hoc and mesh network protocols and their integration with the internet. *Emerging Wireless Technologies and the Future Mobile Internet*, *54, 5–10*.
75. Zhu, L. M., Schuster, P., & Klinge, U., (2015). Mesh implants: an overview of crucial mesh parameters. *World Journal of Gastrointestinal Surgery*, *7*(10), 226.

Chapter 3

Introduction to Network Layer

CONTENTS

3.1. INTRODUCTION

This chapter includes a set of routing protocols designed for WMNs. As a result, we will know how to obtain network topological knowledge, which routing metrics may be utilized, and, most significantly, how to combine these elements using routing path optimization techniques in different routing procedures (Akyildiz et al., 2005). We will also learn about the rules to be followed while developing novel routing procedures.

Ad hoc networks and WMNs have a lot of properties in common. As a result, routing techniques designed for ad hoc networks may often be used for WMNs. For instance, Firetide Networks' mesh routers utilize TBRPF (topology broadcast based on reverse-path forwarding) procedure, Microsoft's mesh systems utilize DSR (dynamic source routing), and several other firms utilize AODV (ad hoc on-demand distance vector) algorithm-based routing procedures (Ishmael et al., 2008; Lavanya and Jeyakumar, 2011). AODV is also a critical component for the routing system of IEEE 802.11s (Figure 3.1) (Sivanesan and Mazzarese, 2006).

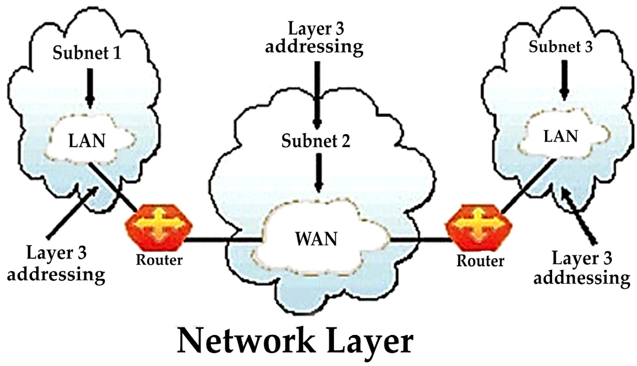


Figure 3.1. Demonstration of network layer.

Source: https://www.assignmenthelp.net/network-layer-assignment.

Owing to the presence of several routing procedures for multihop wireless connections, particularly cellphones ad hoc networks, the structure of routing procedures for WMNs remains a hot topic of study for a variety of reasons (Conti et al., 2015).

- To increase the efficiency of routing procedures, novel routing designs must be found and implemented. The number of hops and quality of the connection are the most often utilized designs for routing procedures. But they do not fulfill the demand of routing for WMNs since the best route relies on a variety of structure goals and WMN network features.

- Higher mobility through all nodes is a key problem for routing in MANETs (mobile ad hoc networks), and complex processes are required to enable this mobility. WMNs, on the other hand, do not require this complexity since mesh routers often have limited mobility (Conti and Giordano, 2014). To obtain good efficiency in MANETs, effective, and light routing procedures must be devised.
- Several multihop wireless networks routing techniques identify the fundamental MAC procedures like a translucent sheet to navigation. But, to increase the efficiency of routing procedures in WMNs, cross-film contact should be studied.
- The requirements for the performance of power in MANETs and WMNs are significantly different. Backbone nodes in a WMN with no power limitations, but participating nodes often want the help of a good energy routing procedure. Because of these changes, routing methods intended for MANETs cannot be suitable for WMNs (Gupta et al., 2015).

Because of the characteristics of WMNs, we think that a routing procedure for WMNs should follow the structure rules outlined in Section 4.2. WMN network film procedures must be adaptable to changing network architecture, traffic load fluctuations, as well as other unknowns. In a multihop wireless mesh setting, WMNs face even more serious difficulties as compared to a One-hop wireless system due to the wireless media and disturbance between various nodes (Park et al., 2017). For instance, a connection may be quickly broken, necessitating the need for a procedure of routing with effective and quick implode capabilities. Sustaining reliable system topologies and routing pathways in WMNs is generally difficult.

In WMNs, the routing protocols must take into account the possibility of an unstable network design owing to the multihop wireless atmosphere while choosing a routing pathway. Furthermore, allotment of resources, disturbance minimization, and speed adaptability across several hops are all interconnected among routing path assortment (Khan et al., 2018). The efficiency of a routing algorithm in a multihop wireless mesh surrounding is manageable because movement in WMNs becomes less complicated than in MANETs. This is an additional benefit for constructing procedures for WMNs and causes the efficiency of a routing procedure manageable in a multihop wireless mesh atmosphere. WMNs, on the other hand, face different routing protocol technical problems than MANETs (Desai et al., 2007; Khan et al., 2018).

3.2. ROUTING CHALLENGES

A routing algorithm may be defined as a solution to the issue: assuming any target and supply, identify the optimal routing pathway which meets all of the limitations, including network design and interruption (Razzaque et al., 2008).

The optimality rules state that when an intermediary Node R is on the most favorable pathway $p_{X,\ Y}$ from Node "X "toward Node "Y," then the optimum path $p_{R,\ Y}$ from "R" toward "Y" should also be on the similar route like $p_{X,\ Y}$. The best pathways among all inputs to a target create a sink tree, anchored at the target, depending upon the idea. It is worth noting that a sink tree is not always distinct since many routing pathways are available from the similar input to the same target, all of which achieve similar efficiency. Consequently, a procedure of routing is the act of identifying various sink trees and using those trees to construct a routing pathway for any input and target (Zhang et al., 1993).

But the routing issue is far more difficult in practice, particularly when combined with a multi-hop wireless network such as WMN. The considerations listed below create routing a much difficult process than just identifying routing pathways depending upon sink trees.

The network geometry might be unstable and changeable. The following are the primary reasons:

- Because of turbulence, fading, and other factors, linkages among nodes might go vertically and horizontally (Tilston et al., 2015). This is especially true in a wireless network. Various nodes in a similar network may have various views of the network architecture as a result of such connection changes.
- The network design might vary owing to node movement or other node actions like connecting or exiting the network, much like connection changes.
- It cannot be viable to select a routing pathway simply depended on network design, based on the routing efficiency objectives.

The following are examples of practical cases (Fortz et al., 2002):

- The matrix of routing is most important than a geometrical factor. When just numbers of hops are taken into account, the selection of routing pathways is simply concerned regarding network design. But, when additional routing variables, such as latency, are taken into account, the selection of routing pathways is impacted not just by network design as well as by influence via nodes without being upon the assorted routing pathways. These routing variables introduce two difficulties: (a) choosing the first routing pathway affects the choice of the second routing pathway; and (b) deciding on a routing pathway affects the allocation of resources methods such as allocation of the channel, media authentication, power management, etc. (Fortz et al., 2002; Fan and Machemehl, 2006).
- To accomplish load balancing, routing pathway assortment must take into account traffic patterns in the network. Traffic patterns, on the other hand, are a product of routing. As a result, load balancing and routing are intimately connected. Since a traffic load connection affects many connections in the coverage area; the situation is significantly more difficult with WMNs.
- For some routing issues, there cannot be an optimum solution. Routing, as previously stated, is linked to a variety of other services, like allocation of resources techniques. Furthermore, the choice of the first routing pathway can be influenced by the choice of the second. Due to the complex optimization issue and the possibility of contradiction restrictions, an optimum solution cannot be possible (Akyildiz et al., 2006).

Routing is generally formulated as a worldwide or centralized optimization issue when it is studied in the context of improvement. A real routing algorithm does not follow quite an approach. As a result, a further difficult problem in routing is determined like how to build a dispersed routing protocol that approximates the optimal solution of the worldwide routing protocol (Azzoug and Boukra, 2021).

3.3. DESIGN PRINCIPLES

Certain considerations must be addressed in the design of routing algorithms to address the aforementioned difficult challenges:

- **Keep the Network Design Stable and Constant:** There are two ways to deal with network design inconsistencies. The first is to create a routing algorithm competent in identifying and fixing discrepancies. Taking into account the dispersed network design of WMNs, this technique typically enhances the complication of a routing algorithm and diverges from the best outcome. As a result, relying on a design discovery technique to obtain a constant design of the network is a more viable method. Although this method is a component of a routing algorithm, it must be used in conjunction with design control and management techniques. The mesh routers in WMNs, particularly infrastructure WMNs, prefer to be stable, allowing connections to be dependable for long periods (Gungor and Lambert, 2006). Thus, a design detection technique may be developed to make certain that all nodes with a constant picture of the network design. Moreover, the preceding techniques, if geographical data is accessible, should be used to correct for network design inconsistency.

- **Performing Continuous and Adaptable Routing:** A routing system for WMNs should be adaptable to changing network circumstances, therefore routing pathways should be continuous rather than stable. Varying network topology or dispersion of traffic are examples of dynamic circumstances. Within a given period, the network algorithm may be controlled to be static and constant; however, it can vary between various periods. To record these variations, a routing system must be adaptable (Pfrommer et al., 2014). The dispersion of customers, their needs, and traffic frames are all factors that influence traffic dispersion. As a result, since traffic is not always routed evenly throughout the network, a routing system must be adaptable for changing traffic circumstances. Unusual variations in the network design, like connection and node breakdown, external network interventions, and so on, must be accommodated by a routing algorithm.
- **During the Development of Novel Routing Matrices:** The count of the hop is amongst the first routing metrics utilized in wireless devices. It is a basic measure, and a routing system dependent on minimal count of hop may always function for WMNs while still being simple. Yet, such a routing algorithm can result in a significant efficiency gap between its real efficiency and the desired efficiency. Ensuring QoS, optimizing resource usage, and boosting network output are usually the efficiency objectives of a routing algorithm for WMNs. Due to the following common

issues; a routing system focused on the minimal count of hop tries to work against these aims (Nandiraju et al., 2007):

– Minimum because traffic flows continue to imitate the similar routing pathway, a lower count of the hop might reduce delays;
– The optimal routing pathway is not always the one with the fewest hops, because connections on a routing pathway with more hops can give a high transmission speed; encounter fewer interruptions, and so on;
– Although the minimal count of the hop does not allow for interactions among various routing pathways, however, this is always the scenario with WMNs (Figure 3.2).

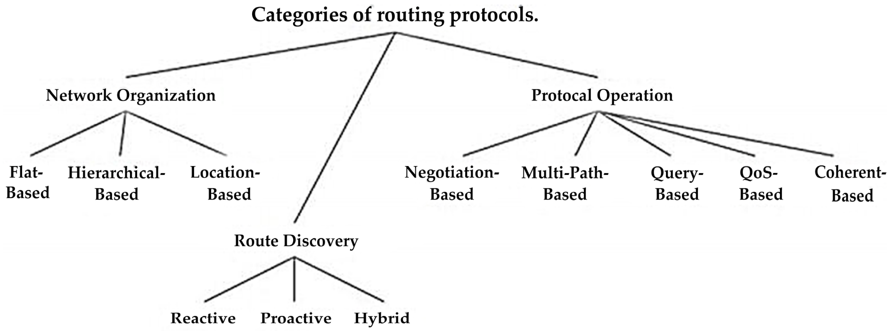


Figure 3.2. Groupings of routing protocols.

Source: https://www.intechopen.com/books/wireless-sensor-networks-insights-and-innovations/routing-protocols-for-wireless-sensor-networks-wsns-.

Notwithstanding such issues, due to its simplicity, the count of the hop is still widely employed in various routing systems (Asgarieh and Lin, 2019). Furthermore, several routing algorithms continue to utilize the count of the hop like the primary routing measure while adding in improvements to increase efficiency. However, creating novel routing measures for WMNs is important if the efficiency targets are to be reached. Because a routing algorithm may incorporate many routing measures, these routing measures do not preclude the count of the hop as one of the routing measures.

- **Taking into Account the Exchange Among Single-Film Solutions and Cross-Film Design:** The choice of a routing pathway in WMNs is heavily influenced by resource allotment in the MAC film and the quality of connection supplied by the physical film. As a result, cross-film interactions among the MAC levels and the routing, as well as the physical film, are unavoidable (Liu et al., 2011). Cross-film design may be used to account for these kinds of connections. Because there is no visibility in the network, this method makes the procedure more complex to implement. Another way to think about cross-film interactions is to translate the connections or restrictions of various procedure films onto a routing measure (Liu et al., 2011; Park et al., 2017). As a result, physical or MAC film and routing concerns are separated, although its connections are still taken into account via the routing measure. The routing metric must be designed in such a manner that the continuous connections or limitations among various protocol levels are correctly represented throughout this method. For instance, when a connection quality-dependent routing metric is formed that also considers the transmission speed, medium access control (MAC) method, and interruption, routing may utilize this connection quality-dependent routing metric to find out the routing pathways without having to work straightforwardly with a physical or MAC film scheme.

- **Developing Distributed Routing Protocols:** In WMNs, the choice of the first routing pathway is influenced by the choice of the second routing pathway. Because of this inter-path interaction, the whole network's routing routes must be calculated using a similar optimization method. This typically demands the use of a worldwide optimization technique. A centralized routing method dependent on worldwide optimization is not feasible for actual application, thus a dispersed routing protocol is preferable (Wendel and Bisch, 1984). Concepts on dispersed routing protocol are required to design such a dispersed system. It is also crucial to ensure that (a) the distribution method is a good estimation of the centralized solution, and (b) the worldwide optimization is not even an inadequate issue.
- **Making Sure the Routing Scalability:** Like a routing algorithm is supposed to function effectively in WMNs of varying sizes, scaling is always an issue. The routing algorithm should have the smallest possible overhead. Overhead may have a compounding effect on data traffic and substantially decrease the efficiency of

a data traffic routing pathway. Working in a decentralized instead of centralized manner is recommended. A further successful strategy is to use hierarchical routing to divide the network into various sectors: every hierarchical level has its routing job for its corresponding network sector. The difficulty with this technique is coordinating the inter-routing of various sectors. On the other hand, hierarchy routing has been promoted by WMNs because it enables WMNs to expand in size without putting undue strain on routing algorithms (Akyildiz et al., 2005).

- **Supporting both Mesh Clients and Mesh Routers Flexibly:** Taking into account the minimum movement and absence of power usage limitation in mesh routers, a significantly easier routing algorithm than current ad hoc routing algorithms may be created for mesh routers. Mesh client routing must take into account energy performance and portability, but not the routing approach established for MANETs. Conversely, mesh routers and mesh clients should work together to simplify the routing algorithm (Reina et al., 2018).

The main elements of a routing algorithm, as mentioned in the above topology rules of a routing algorithm in WMNs, are network design identification, routing measurements, and routing protocols. These 3 elements are broken down into 3 subsections throughout the rest of this chapter.

This must be noticed that a routing algorithm generally contains additional supportive elements or requires aid from other procedures to incorporate the abovementioned 3 elements in a similar protocol (Medvidovic and Taylor, 2000; Reina et al., 2018). To control network design development, for instance, a signaling technique can be needed. Additionally, processes for transferring routing-related signals throughout the network should be developed. Such supportive elements, although, are not examined individually in this chapter. Conversely, they are brought up whenever they are needed.

3.4. TOPOLOGY FINDING FOR ROUTING

The development of network designs is influenced by a variety of variables. Quality of connection, network node movement, node accessibility, network development, etc., that are all common instances. Such variables have an influence on the topology and efficiency of a routing system due to network topology. As a result, a routing algorithm's ability to accurately identify network topology data is vital (Dhamdhere et al., 2012).

The process of discovering topologies may be conducted in a decentralized or centralized manner. Since WMNs are essentially a decentralized multihop network, the decentralized discovery technique is a superior fit for them. A routing algorithm receives network design knowledge and other relevant data through the discovery of topology (Akyildiz et al., 2001).

The goal of topology discovery is to locate updated mesh node topological data. To disseminate and by gathering topological data, an effective exchange of data methods is required, and the following challenges should be taken into account:

- **Frequency of Data Swap:** The periodicity should be in a finer granularity to acquire design changes caused by network activity. Although, if the periodicity is set excessively higher, excess data would travel across the network, and as a result wasting of valuable WMN resources (Čičić, 2008).
- **Signaling Messages' Contents:** Whenever a node swaps topological data with its surroundings nodes, the data used in a notification message is determined by the routing algorithm's functioning processes. A routing algorithm must utilize such little topological data as feasible to decrease protocol cost (Modiano and Narula, 2001).
- **Techniques for Data Swap:** This is focused on determining the main effective method of exchanging data. Whenever connections are stable, broadcasting can be a feasible alternative since information may be delivered to all companions in a single transmission. Broadcasting, on the other hand, is ineffective when the quality of the connection is unstable; without response, information might easily disappear. While retransmissions may be used to enhance the chances of getting similar information, owing to the unavailability of acknowledgment, it is impossible to predict how often retransmissions are required to ensure information receiving at all nodes. Unicasting must be utilized to swap topological information to overcome this problem. Whenever unicasting or streaming is used, the tradeoff between messaging cost and topological data reliability must be considered (Wu and Harms, 2001; Krioukov et al., 2007).

Multi-radio or multichannel activities, that are frequent in WMNs, might obstruct topological discovery. In a multi-radio or multichannel WMN, for instance, a routing protocol can be used to decide the task of channel or selection of radio. The topology of the network is unclear to a mesh node earlier than the routing protocol determines routing pathways if the network design discovery is based on the specified channels or radios for connections among mesh nodes. Although, topological data is still required since the routing protocol relies on design discovery to understand all potential configurations in a multi-radio or multichannel WMN before determining the optimal routing pathways based on such morphologies (Lui et al., 2004). To prevent a contradiction among channel assortment and design discovery, collecting network topology data without depending on radio or channel assortment is a good strategy. Neighboring mesh nodes, for instance, may briefly switch to a general channel to swap topological data; subsequently, return to the original channel after the swap is done (Khan et al., 2018; Jia et al., 2019).

The positioning data of mesh routers and even mesh users can be accessible for certain WMNs. Every node's position data must be effectively transmitted to other nodes in such a situation. The incorrect network design can be corrected for or even location-based routing methods may be designed depending on node location data (Nikkhah and Guérin, 2015).

3.5. EFFICIENCY PARAMETERS

A routing algorithm's overall purpose is not only to discover a routing pathway for each (source-target) pair but also to obtain the highest possible efficiency. There are many efficiency parameters and may be established at several levels of network infrastructure (Rault et al., 2014; Ji et al., 2016):

- **Parameters for Single-Flow:** QoS characteristics like latency, packet loss relationship, and delaying fluctuation, as well as other factors like the count of the hop, single-flow capacity, and intra-flow disturbance, are all the parameters of single-flow.
- **Parameters for Single-Node:** Calculation complications and the efficiency of power are two aspects of a node's effectiveness.
- **Parameters for Single-Connection:** Performance factors like the quality of connection, channel usage, transmission speed, and traffic must be evaluated for connections among 2 nodes.

- **Parameters for Inter-Flow:** The parameters of inter-flow describe the connection between various traffic moves on various connections. The disturbance of Inter-flow and fairness are two common manifestations.
- **Parameters for Network-Wide:** A routing algorithm is required to evaluate general network efficiency to guarantee QoS for every flow of traffic, and so must evaluate network-wide characteristics like the total output of the network (Tran et al., 2018).

The aforementioned efficiency metrics may be divided into 2 categories by customers: indirect and direct efficiency factors. QoS, the efficiency of power, or throughput are all part of the first set. Consumers may see these characteristics since they indicate efficiency that may be immediately observed by them. All other characteristics are in the latter category since they are not accessible to consumers and have only a tangential influence on QoS, the efficiency of power, or throughput (Babber and Randhawa, 2017).

It is worth noting that the criteria listed in previous sections are neither independent nor redundant. As a result, they cannot be handled individually, and the first variable cannot take the place of the second. As a result, capturing such cross-related factors with single routing parameters is a fascinating issue. Although, these factors are so varied and exist at various levels of the network architecture, developing a routing parameter that captures all of them is a tough research challenge. To obtain this objective, theoretical advances are required (Ozonoh et al., 2020). All of the routing parameters presented thus far only capture a portion of the efficiency metrics listed above. All present routing methods do not offer optimum efficiency for consumers and the whole network due to this limitation in routing parameters; only the performance metrics recorded by the routing parameter are improved. Following that, we will go through the accessible routing parameters for WMNs (Francesco et al., 2011).

3.6. ROUTING METRICS

To calculate the "Distance" between any destination and source, a routing algorithm must rely on a certain routing parameter. A routing protocol determines route pathways depending on these distances. By using various routing measures, the real meaning of the term "distance" changes accordingly. When the count of the hop is employed as a routine measure, for instance, the "distance" among a destination and a source is defined as the hop-count these 2 nodes. Various kinds of distances should be utilized in a routing algorithm based on the efficiency objectives, requiring the development of various routing parameters (Baumann et al., 2007). If the hop-count is less significant than the delay, the routing parameters should be capable to catch the delay on every connection such that the distance of a routing pathway may be expressed by the total delay.

A routing parameter may be designed to collect one or more performance factors. The routing parameter may be calculated in a one protocol film or several protocol films in the latter scenario. As a result, the routing parameter may be characterized into three categories (Youssef et al., 2013):

- A measure for a single set of performance metrics;
- For numerous performance parameters, a single-protocol-film measure is used; and
- For various performance factors, a multi-protocol-film metric is used (Figure 3.3).

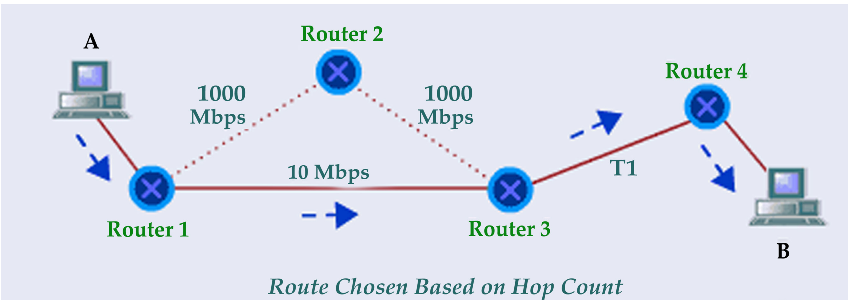


Figure 3.3. Routing depended on the number of hops.

Source: http://units.folder101.com/cisco/sem2/Notes/ch6-routing/routing.htm.

3.6.1. The Count of the Hops

The count of the hop is a basic routing measure since it just requires knowing if a connection is present or absent. The count of the hop, though, could not give useful data about a connection due to its on/off characteristic, like the loss of packet, the quality of connection, etc. As a result, the count of the hop routing algorithm only examines one performance factor: the minimal count of the hop of every routing pathway (Johnson and Hancke, 2009). The minimal count of the hop is a suitable criterion to discover a decent routing pathway in just a few circumstances. Consequently, in certain situations, the minimal count of the hop of a routing procedure is insufficient to provide excellent efficiency. Nonetheless, due to its ease, the count of the hop is employed in several present WMN routing systems. The count of the hop is a helpful routine measure in certain application settings where accessibility rather than optimal speed is the primary goal (Sanmartin et al., 2018).

3.6.2. Per-Hop RTT (Round Trip Time)

Delivering unicast probe packets to adjacent nodes and measuring the hours spent on the probe-ack operation, as described in Ahmed et al. (2013) may be used to determine per-hop round trip time (RTT). As each specimen may not represent the real connection state, the weighted moving average technique is typically needed to provide a smooth assessment.

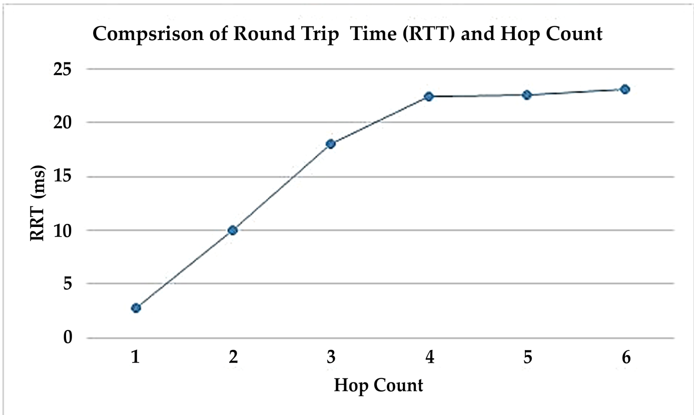


Figure 3.4. Examination of hop count vs RTT.

A routing algorithm picks a routing pathway having the lowest total of RTT of all connections on the pathway based on per-hop RTT. The packet loss fraction in a connection, the queuing time and load of the traffic in 2 nodes on the connection, and the conflict state in all adjacent nodes may all be captured using per-hop RTT. Moreover, its usefulness is limited by 2 issues (Draves et al., 2004). The first is that per-hop RTT is very reliant on a load of traffic or queuing latency that disrupts per-hop RTT accuracy and may simply lead to path instabilities. If a different line is formed for probing packets, the connection performance may be properly measured; however, the load of the traffic may not be reflected. Adopting the connection measuring technique described is one solution to this issue (Kim et al., 2006). A further issue is that the weighted moving average technique is used to determine the precise per-hop RTT calculations. If the calculations variances are significant, the per-hop RTT will not be able to obtain a valid result, regardless of the weight used in the weighted moving average technique. Since a node must transmit probe packets to all its adjacent nodes, the extra cost of the probe-ack operation of per-hop RTT must be properly justified. Per-hop RTT collects per-connection efficiency parameters, even though the calculation is done at the network film (Figure 3.4) (Amish and Vaghela, 2016).

3.6.3. Per-Hop Packet Pair Delay (PPD)

A node's per-hop packet pair delay (PPD) is calculated by transfer 2 straight probing packets to its adjacent nodes. One probe is a tiny packet, although the other one is huge. Whenever the adjacent node gets such 2 packets, it determines the time difference among them and relays this data to the probe node. This technique was first introduced for wired networks and then researched for WMNs (Keshav, 1995; Draves et al., 2004). Per-hop PPD calculation is lesser influenced by lining delays or a load of traffic in a node because comparable delay is utilized to assess the per-hop latency. Moreover, as the ability to deliver probe packets on a connection among 2 nodes is equally dependent on the lining delays of other adjacent nodes, such influence remains.

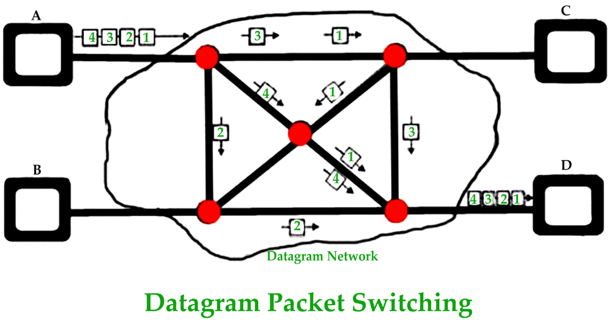


Figure 3.5. Computer network's packet switching and delays.

Source: https://www.geeksforgeeks.org/packet-switching-and-delays-in-computer-network/.

That is particularly real in the case of a mesh network. If Node "A" transmits a probe packet to node "B," for instance, if "A" is adjacent to "C" is simultaneously transmitting a large amount of traffic to "A," "A" must postpone its probe to "B." As a result, per-hop PPD must still account for route uncertainty. Furthermore, because more probe packets are required, this measuring technique has a higher percentage cost than per-hop RTT. Its efficiency is likewise based on the weighted moving average technique, which presupposes that calculation variance is low (Draves et al., 2004). Per-hop PPD, like per-hop RTT, collects just per-connection efficiency factors (Figure 3.5).

3.6.4. ETX (Expected Transmission Count)

The estimated count of broadcasts until a packet is delivered successfully over a connection is known as the expected transmission count (ETX). The ETX of a path is the total of the ETX of all connections. On both sides of a connection, the connection ETX may record packet loss and quality of connection. The path ETX may also identify disturbance between connections on a similar path; the bigger the path ETX, the fewer self-interference on the path (Figure 3.6) (Ni et al., 2008).

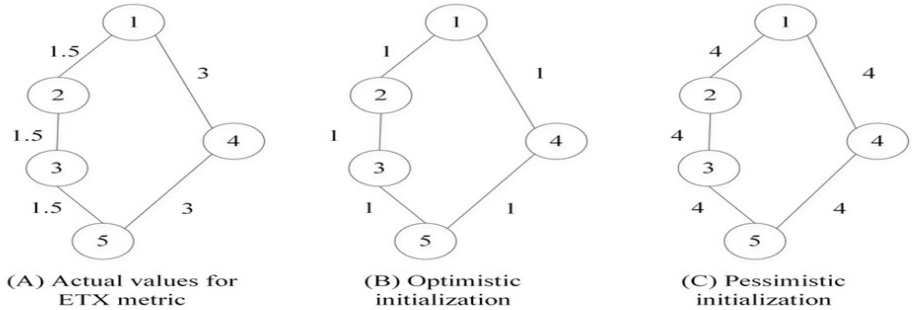


Figure 3.6. Initialization of ETX measurement.

Source: https://www.researchgate.net/figure/Initialization-of-expected-transmission-count-ETX-metric_fig1_315925020.

The ETX is calculated using probe packets. A node transmits a transmission probe notification to its adjacent nodes every period of τ seconds. Every adjacent node keeps track of the count of received probe notifications (which have now been labeled) for the time duration of "w" seconds, where "w" is greater than "τ." As a result, transmitting a packet from the probe node to its adjacent node has a delivery relationship of nw / (w/τ). If a probe node includes the "nw" data from all of its adjacent nodes in the probing packet, every one of those adjacent nodes may calculate the packet delivery relationship from the probe node's neighboring. ETX = 1/

(dr × df) is computed using the delivery relationship in both reverse and forward directions, represented by dr and df, accordingly. Since probing messages are telecasted instead of unicast, the ETX has a smaller extra cost (Jevtic and Malnar, 2019). Because the ETX does not track latencies, the measurement dependent on probing notifications is unaffected by node lining delays. The ETX, on the other hand, has several flaws. Since transmission messages often employ better resilient coding methods and modulation, and hence have lower broadcast rates, probing messages have distinct packet loss ratios than unicast messages. The 2nd issue is that the ETX fails to account for changes in packet size for various traffic patterns as well as varied connection capabilities (Couto et al., 2003).

The 3rd issue is that the estimating technique of ETX, which depends on the average loss ratio, cannot be correct; nevertheless, wireless connections frequently undergo busty losses. Furthermore, while an ETX route assures that packets travel along a higher capacity pathway with good connection quality and little self-interference, such characteristic helps to generate blockage pathways in the network until a balancing of load mechanism is devised that operates in parallel with the ETX routing algorithm (Draves et al., 2004).

Regardless of the aforementioned issues, the ETX may represent per-connection efficiency and, to a limited extent, per-flow efficiency, as well as network-wide efficiency.

3.6.5. ETOP (Expected Transmission on a Path)

In several routing algorithms, the location of a connection is not taken into account in routing parameters while choosing a routing pathway. When the ETX is utilized to find out a routing pathway, for instance, only the ETX value of every connection matters. On the other hand, while deciding between two routing options, the sum of the ETX value is the only factor to evaluate (Jakllari et al., 2011; Li et al., 2012). This seems to be valid if the connection-film supports an unlimited number of retransmissions since a retransmitted packet has a similar effect regardless of which connection retransmissions occur. End-to-end retransmission must be performed if the connection layer has a restricted number of retransmissions. When comparing 2 connections, even though their ETX is identical, the one nearer to the target might cause more transport film retransmissions, implying that when this connection is chosen, it will result in poor efficiency.

The expected transmission on a path (ETOP) overcomes the previously mentioned issues by accounting for the relative location of a connection on a routing pathway while calculating the pathway's routing expense (Jakllari et al., 2011). T_n represents the cost of a routing pathway with n connections from node V_0 toward node V_n. The required number of end-to-end tries for a package to be transported end-to-end over this routing channel is considered to be Y_n. Furthermore, in an end-to-end try j, and M denotes the number of connections that a packet has traveled before being discarded by the connection film and H_j denotes the number of connection-film transmissions at node j. The ETOP of a routing pathway is the anticipation of T_n and which is provided by:

$$\mathbb{E}[T_n] = \left(K + \sum_{j=0}^{n-2}(\mathbb{E}[H_j|H_j < K]\mathbb{P}[M > j|M < n])\right) \times \mathbb{E}[Y_n - 1] + \sum_{j=0}^{n-1}\mathbb{E}[H_j|H_j < K] \quad (1)$$

ETOP captures the overall amount of connection-layer broadcast of a particular routing pathway under all feasible end-to-end tries, as indicated in the above expression (Youssef et al., 2013).

ETOP may enhance transport layer performance when compared to ETX since a routing pathway with the fewest total connection-layer retransmissions is chosen. Furthermore, to calculate ETOP from other easily measurable quantities, a specific method is required. The approximate numbers of transmissions in the connection layer are used to develop an equation for calculating ETOP (Jakllari et al., 2011). It is obtained using 2 key hypotheses: connection-layer transmission follows a similar random procedure for all nodes, and connection-layer broadcast in various tries is unbiased and has a similar distribution. Since connections encounter varying interference, route loss, fading, and other effects in a WMN, such 2 suppositions are false.

3.6.6. ETT (Expected Transmission Time) and WCETT (Weighted Cumulative Expected Transmission Time)

The expected transmission time may be thought of as a more advanced form of ETX. The expected transmission time evaluates the influence of both packet size and connection quality as following, depending on ETX: ETT=ETX. The packet size is S/B, in the relation pocket size is denoted by "S" and the connection bandwidth is denoted by "B" (Draves et al., 2004). As a result, the expected transmission time represents the predicted packet broadcast time for a given connection. The anticipated broadcast time for a routing pathway may be calculated as the total of the expected transmission time of all connections on the pathway. Furthermore, in WMNs with several radios at certain nodes, such a strategy fails to account for channel variability. A routing measure called weighted cumulative expected transmission time (WCETT) is presented in, as a solution to this problem (Draves et al., 2004):

$$\mathrm{WCETT} = (1-\beta)\sum_{i=1}^{n} \mathrm{ETT}_i + \beta \max_{1\le j\le k} X_j \tag{2}$$

In the above equation, the hop-count on a routing pathway is denoted by "n," the number of obtainable channels for the multi-radio function is denoted by "k." Furthermore, , thus, β max1≤j≤kX_j locates the blockages of the channel of a given routing pathway. As a result, the 1st term in Eqn. (2) examines the overall projected broadcast time of the routing pathway, whereas the 2nd term examines the broadcast time on the blockage channels. The WCETT analyzes the equilibrium among total routing latency and channel variability usage in this manner (Ma et al., 2007).

The expected transmission time improves ETX efficiency by considering packet size and connection bandwidth when calculating broadcast time. Furthermore, since it utilizes the same estimate technique to ETX, it suffers from the same issues as ETX, such as incorrect estimation, blocked paths, and so on. For two purposes, the WCETT does not applicable to WMNs dependent on single-radio several channel process (Zhou et al., 2006):

- Telecast probing messages cannot be transmitted on several radio channels at the same time; and
- The expected transmission time of a connection may be compared to the channel switching time.

3.6.7. ENT (Effective Number of Transmissions)

To account for both the average loss ratio and the variation of connections on a routing pathway proposes *mETX* =exp (, while σ^2 and μ are the variance and average of the packet loss ratio, respectively. A performance-aware routing measure called an effective number of transmissions (ENT) is generated from this notion. In the ENT, a path's end-to-end packet loss ratio cannot surpass a certain limit. Two variables are generated to meet this QoS criterion. The 1st one is the upper bound of anticipated broadcast M (Koksal and Balakrishnan, 2006).

The 2nd one is a variable that must be provided in mETX to obtain the effective number of transmissions: *ENT* = exp $(\mu + 2\delta\sigma^2)$. Furthermore, if the ENT is greater than log (M), the weight of the related connection must be infinite. The connection quality of the ETX estimates accuracy is improved by the ENT, which also provides performance-aware routing. Furthermore, since it is constructed on top of the ETX, the ENT still suffers from the flaws of the ETX (Koksal and Balakrishnan, 2006).

3.6.8. MIC (Metric of Interference and Channel-Switching)

Intra-flow interference and inter-flow are both taken into account by the metric of interference (MIC) and Channel-switching. For the source of inter-flow interference, an IRU (interference-aware resource usage) is suggested for a connection one connecting nodes "i" and "j" utilizing route "c" as:

$$IRU_i = ETT_i + N_{ij}(c) \tag{3}$$

In the equation, $N_{ij}(c)$ is the number of nodes obstructed by node "j" and node "i" as they broadcast in channel c.

A channel switching cost (CSC) parameter is developed to account for intra-flow interference. If the output and input hops for a node "i" on a routing pathway utilize distinct channels, CSCi is equal to w1; otherwise, CSCi is equal to w2, where w2 is greater than w1 (Yang et al., 2006; Ghannay et al., 2012).

The "metric of interference and channel-switching" of a route p is calculated using the 2 parameters mentioned above. And the equation is given by:

$$MIC_p = \frac{1}{N \times \min(ETT)} \sum_{\text{link } l \in p} IRU_l + \sum_{\text{node } i \in p} CSC_i \tag{4}$$

In the equation, the total number of nodes in the network is denoted by N.

MIC has several flaws, although it seeks to account for both inter-flow and intra-flow interference. First, the expected transmission time is a variable that takes into account all of a link's interference, casting doubt on the reliability of the IRU usage. Secondly, the intra-flow interference CSC does not represent real interference, but rather distinguishes the similar channel from communications on various channels on subsequent hops. The CSC does not track the quality of the connection. Furthermore, CSC does not represent the real channel switching time (Malnar and Neskovic, 2011; Malnar et al., 2014).

3.6.9. BLC (Bottleneck Link Capacity)

The expected busy time (EBT) of broadcasting a packet on a connection is used to calculate bottleneck link capacity (BLC). The packet loss rate (PLR) and broadcasting method in the MAC film may be used to calculate the EBT. For instance, when an IEEE 802.11 MAC uses an RTS-CTS-Data-Ack handshake for packet broadcasting, the EBT may be computed as:

$T_{handshake} /(1 – e_p)$

In the above ratio, the total transmission time of one RTS-CTS-DataAck is denoted by $T_{handshake}$, and the PLR is denoted by e_p. The ratio among the EBT and spare time is used to calculate a link's residual capacity. If the link's residual capacity "i" is LC_i, by examining path P, subsequently the relation of BLC is calculated as:

$$\mathrm{BLC} = \frac{\min_{i \in P} \mathrm{LC}_i}{\mu^K} \quad (5)$$

In the equation, the length of the routing pathways P is denoted by K and a fine-tuning parameter is denoted by μ. The BLC denotes the remaining capacity of a routing pathway's bottleneck connection. Furthermore, a lengthy routing pathway is fined by dividing the minimal residual capacity by a specific number (Dai et al., 2019).

Balancing of load in connections has also been considered since busy time is taken into account in the BLC. Furthermore, since the BLC considers the minimal residual capacity, the self-interference of a routing pathway is not taken into account. On the other hand, the bottleneck connection might have a similar residual capacity as 2 routing pathways with various self-interferences. Interference from other routing pathways causes a similar issue (Ros and Tsai, 2010).

3.6.10. EDR (Expected Data Rate)

TCD (expected transmission contention degree) and the ETX are combined into a single routing measure in the expected data rate (EDR). The expected transmission contention degree of a connection is the amount of time spent over a certain period retransmitting unacknowledged packets. When examining connection "k" on a routing pathway, if the total of expected transmission contention degrees of connections which conflict with connection "k," then the EDR of connection "k" is:

$$\text{EDR}_k = \frac{\Gamma}{I_k \ \text{ETX}_k} \quad (6)$$

where; "τ" is the utmost broadcasting rate of the connection k. For the EDR of a routing pathway, it is termed the EDR of the bottleneck connection.

The EDR has a few flaws. Firstly, the ETX X combines two highly related variables: (i) the ETX; and (ii) the expected transmission contention degree (Zhong et al., 2019). In reality, if the ETX is high, the expected transmission contention degree is huge as well, assuming the equal packet length. As a result, it is unclear why the expected transmission contention degree and the ETX must be mixed as in Eqn. (6). Secondly, even though the connection rate is taken into account in the measurement, it ignores the reality that each connection has numerous rates available rather than just the maximum rate. The 3rd issue with the EDR is that determining the interference range of a specific connection "k" is challenging, making I_k difficult to calculate (Cummins et al., 1986).

3.6.11. Less Overhead Routing Variable

A technique for transmitting probe messages or gathering adjacent details is required to assess routing parameters. This may result in overhead. As a result, several studies have suggested deriving a routing variable from accessible detail in a MAC layer's MIB (management information base) (Karbaschi and Fladenmuller, 2005; Ma et al., 2005).

To calculate the routing measure, proposes the LQCA (link quality and congestion aware) parameter relying on RTS Failure Count (fc_{RTS}) and the ACK Failure Count (fc_{ACK}). First of all, a node's frame broadcasting performance is calculated as $FTE = 2/(fc_{ACK} + fc_{RTS})$ (Karbaschi and Fladenmuller, 2005). The computations of all nodes in a path make up the path's FTE. Second, a link quality and congestion-aware routing variable is described as $FTE_P \times (1 - hop_P /N)$, wherein FTE_P represents the FTE of the routing pathway P, hop_P represents the hop-count, and N represents the count of nodes in the network. As a result, LQCA measures the congestion and the quality of connection using an ACK and RTS failure counts, as well as hop counts to penalize lengthy routes. The efficiency of the MIB variable determines the correctness of this routing parameter (McQuillan et al., 1980). Furthermore, failure numbers are often specified as per node rather than per connection. As a result, since these failure numbers are mean overall connections from a similar node, the connection-related quality is inaccurate. The MIB network allotment vector (NAV) is utilized to calculate a routing parameter (Ma et al., 2005). Within a certain period, a mean network allotment vector count (NAVC) is computed for every node. The network's congestion state is assessed and matched to latency and bandwidth efficiency using this average NAVC. If the average NAVC is greater than 0.65, the node is deemed congested, and it increases the route NAV total for every routing pathway involves in this node. If it is less than 0.2, although, it makes no addition to the path NAV total. Because the average NAV is a per-node statistic rather than a per-link measure, it does not indicate network performance. Furthermore, it is unclear how precise the NAV Count may be for expressing QoS factors like packet loss or latency (Alzamzami and Mahgoub, 2018).

3.6.12. Airtime Cost Routing Metric

The airtime cost measure is recommended as a standard routing parameter in IEEE 802.11s draught to find an effective radio-aware pathway between all the possible pathways (Sivanesan, 2006). It represents the number of route resources used to send a frame across a certain connection. The optimal pathway is the one with the least amount of airtime expense. The airtime cost C_a for every connection is computed as:

$$C_a = \left[O_{ca} + O_p + \frac{B_t}{r} \right] \frac{1}{1 - e_{pt}} \tag{7}$$

In the above equation, B_t, O_p, and O_{ca} are constants their values rely on the utilized broadcasting tech. the channel access overhead is denoted by O_{ca}, the protocol overhead is demoted by O_p, and the number of bits in a test frame is denoted by B_t. The e_{pt} is the rate of bit in Mbit/s and "r" is the frame error rate for the test frame size B_t, correspondingly (Barz et al., 2015).

The above-mentioned routing parameters are given in Table 3.1, together with their various features. Several routing parameters, as indicated in the table, attempt to measure link-layer efficiency parameters utilizing a network film technique. The evaluations of the quality of the connection may be performed directly at the connection layer and after that used in the layer of the network to improve such methods. This technique necessitates the inclusion of cross-layer connections in the routing parameters (Wu and Chan, 2010).

3.6.13. Other Problems

Even though WMNs have access to several routing parameters, there are still a few problems:

- A routing variable will not be able to collect sufficient network metrics for a routing algorithm to maximize network efficiency. Available routing parameters, for instance, are mostly generated from connection characteristics to substitute hop-count. Some routing parameters, on the other hand, have explored how to calculate QoS or performance factors in a routing measure, which is essential in WMNs.
- Although considerable research has been completed for some routing measures, efficiency comparisons among various routing variables require more investigation (Draves et al., 2004).
- Several available routing parameters are still "ad hoc" in construction. On the other hand, there is no justification for why the suggested routing measure may increase network efficiency; often, just simulation results are utilized to establish a routing variable's efficiency. As a result of this architecture, a routing parameter's usefulness can be confined to a specific kind of WMN.
- A route metric's evaluation technique can be inaccurate. It might potentially result in a significant amount of overhead, particularly in a large-scale system.

As a result, further study into routing parameters for WMNs is required. Novel routing parameters, particularly, are required to best serve a routing protocol's improvement aim.

Table 3.1. Comparison of Various Routing Parameters for WMNs

Routing parameters	Captured efficiency Metrics	weaknesses	Benefits	Perform on which films
Per-hop round trip time	queuing delay, Packet loss, contention, traffic load,	Higher cost in transport probings; approximation precision relies on a load of traffic	several connection parameters captured	Network
Hop-count	The number of hops	Minimalcount of the hop is typically not the objective of efficiency	uncomplicated and less cost	Network
Expected Transmission Count	broadcasting, contention, Packet loss,	may have bottleneck connection; the calculation is not precise because of variations among unicast and transmission; can't catch packet loss differences; no balancing of load;	several connection parameters captured, comparative less cost by utilizing transmission	Network
Per-hop packet pair delay	Broadcasting latency, contention, Packet loss,	Higher cost in calculating latency; performance dependent on the measurement accuracy; no load balancing	several connection parameters captured; low impact through a load of traffic	Network
WCETT and Expected Transmission Time	Similar connection parameters of Expected Transmission Count and also connection packet size and bandwidth	Similar issues like Expected Transmission Count; This is not relevant to multichannel functioning on a uni radio.	enhance Expected Transmission Count by taking into account the connection packet size and bandwidth; channel variety is taken into account	Network

Expected transmission on a path	End-to-end tries, connection broadcasting	complexity in deriving the parameters	The position of connection to be taken into account in routing	Connection, Network
Metric of Interference and Channel-switching	further connection parameters such as Expected transmission count, intra-flow & Inter-flow interference,	The technique of integrating expected transmission time & the level of interference is uncertain; it's difficult to approximate the level of interference; channel switching is not taken into account	Consider both intra-flow & Inter-flow interference together with predictable broadcasting time; maintain multichannel process	Network
Effective Number of Transmissions	Packet loss, its discrepancy, end-to-end packet loss	Cost in collecting packet loss and its variances; additional issues of expected transmission count still exist	Most precise approximation of packet loss as compared to expected transmission count; assurance of end-to-end packet loss	Network, connection
Expected Data Rate	Connection parameters as that in expected transmission count, conflict time	Has the similar issues as those in expected transmission count; difficult to find interfering connections	Utilize conflict time of all interfering connections to consider interference	Network
Airtime cost	Resource utilized by a packet on a connection	The extra cost in probing; airtime cost measured by probe message can be various from a packet	measures the impact of the active atmosphere on a connection	connection

Bottleneck Link Capacity	hop count, time, the rate of packet loss, MAC handshake,	The block connection of a path doesn't take into account self-interference	the remaining capability of a connection is taken into account, so the balancing of the load is done circuitously	Network, connection
Network allotment vector count	Mean count of network allotment vector	Has the similar issue as Link quality and congestion aware	No probing is required less extra cost	Connection
Link quality and congestion aware	hop count, ACK & RTS breakdown count	There is no per-link measure; MIB data can't be precise adequate for routing	Only MIB is utilized, no probing required, less extra cost	Network, connection

3.7. ROUTING ALGORITHM CATEGORIES

A reactive or proactive routing mechanism for WMNs is possible. Before any traffic path among 2 nodes, proactive routing establishes a routing pathway between these. Only once traffic is produced among 2 nodes can reactive routing begin to put up a routing pathway for such 2 nodes (Abdulla et al., 2012).

Based upon whether the network's design, connection reliability, the load of traffic, and other factors change, a routing protocol might be dynamic or static. There are several circumstances in which static routing might be useful in a wired connection. Because of node movement, connection unreliability, geometry change, traffic fluctuations, and other factors, routing in a multi-hop wireless connection such as a WMN is generally dynamic. The link-state routing and distance vector routing, which were introduced for wired networks and have formed the foundation of several dynamic routing algorithms for WMNs and MANETs, are 2 prominent dynamic routing techniques. A routing algorithm may be implemented in a centralized, decentralized, or mixed way depending on its routing protocol. For instance, in IEEE 802.11s, the routing architecture offers two centralized and decentralized modes: (1) tree-based routing and (2) AODV-like routing. A hybrid routing method is planned to combines both techniques into a single routing algorithm (Sivanesan and Mazzarese, 2006; Lim et al., 2008).

The present routing algorithm for WMNs may be grouped as per their efficiency improvement goals for better categorization.

3.7.1. A Routing Depended on Hop-Count

Even now, several WMN routing systems also utilize hop-count as their routing measure. While reducing the number of hop counts has nothing to do with WMN efficiency improvement, it does have the benefit of being simple. Additional functions may be more readily added into a routing algorithm with a basic routing technique. A routing algorithm, for instance, may be developed to enable client movement effectively or to adapt an existing algorithm for multichannel functioning (Iannone and Fdida, 2005; Pirzada et al., 2006). Scientists can also experiment with new routing methodologies using the basic routing parameter (Baumann et al., 2007). Furthermore, these entire routing algorithms are supposed to be improved to consider more comprehensive routing characteristics to attain the ultimate objective of optimal efficiency (Figure 3.7).

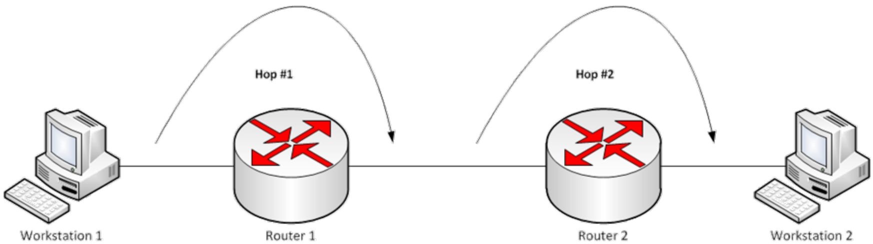


Figure 3.7. A demonstration of hops in a wired network (assuming a 0-origin hop count). The count of hop among the computers, in this situation, is two.

Source: https://www.wikiwand.com/en/Hop_(networking).

3.7.2. Link-Level QoS Routing

Routing efficiency is optimized in certain routing algorithms by reducing the total sum or underclocked link-level routing measure of a routing pathway. Therefore, a user's perception of end-to-end QoS cannot be assured. In such a routing algorithm, QoS is only partially taken into account by a hop-by-hop approach at the link level rather than an end-to-end solution.

Several variables may affect the connection quality, including medium access suppositions, network traffic, disturbances, path quality, and so on. We may evaluate the PLR, retransmission count, and packet broadcasting duration of a connection to determine its effectiveness. For WMNs, several routing procedures that rely on connection quality have been suggested (Draves et al., 2004; Biswas et al., 2005). Interference (both inside the network and outside of the network), the traffic load on various connections, and a link's remaining capacity are all connected to connection quality, although they may not be explicitly reflected by this. As a result, certain link-level QoS-based routing algorithms have been designed with the efficiency improvement objective of explicitly addressing interference, remaining connection capacity, and traffic load balancing (Figure 3.8) (Shen et al., 2006; Song et al., 2006).

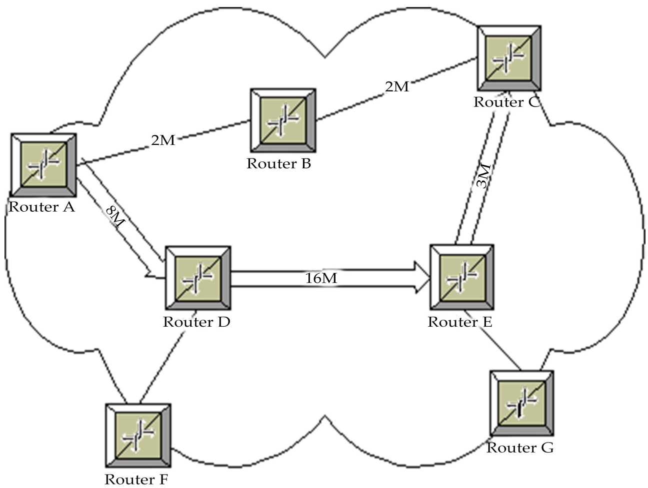


Figure 3.8. QoS-based routing illustration.

Source: https://www.cse.wustl.edu/~jain/cis788-99/ftp/qos_routing/index.html.

3.7.3. End-to-End QoS Routing

In End-to-end QoS, variables are used as an efficiency improvement goal in several routing systems. As a result, such techniques are predicted to outperform routing methods based on link-level QoS in terms of QoS efficiency. Bandwidth, packet loss, and Delay are the most researched end-to-end QoS variables thus far (Lin et al., 2006). A delay-aware routing algorithm is prepared to provide an end-to-end latency limit and guarantees an end-to-end packet loss correlation limit. End-to-end bandwidth allotment is taken into account (Figure 3.9) (Tang et al., 2005; Al-Karaki et al., 2017).

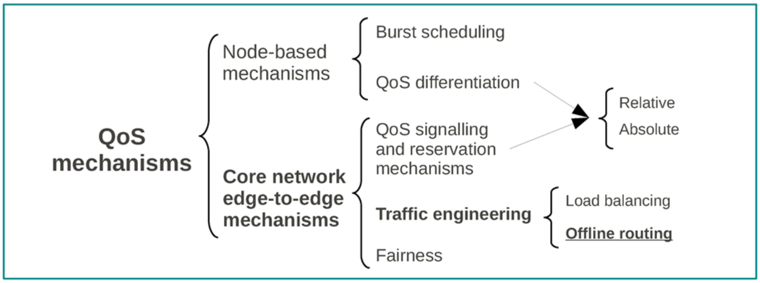


Figure 3.9. Demonstration of QoS mechanisms.

Source: https://www.mdpi.com/1999-5903/2/4/559.

3.7.4. Dependability-Aware Routing

In certain application settings, dependability takes precedence over other efficiency goals. In this scenario, several routing pathways are favorable techniques in which several routing pathways are present to increase dependability. When several routing pathways are present, they may be utilized to deliver traffic at the same time, or just the optimal routing pathway may be utilized, leaving the others as backups. Because only a single routing way is utilized at a time, the former technique may obtain the best traffic allocation across the whole network, whereas the latter technique is easier to maintain because only a single routing pathway is utilized at a time. Duplicates of a packet are transmitted from a customer to the target pathway through different routing pathways (Yuan et al., 2005). An integrated routing algorithm is presented that includes 2 routing pathways, first through core WMNs and the second through consumers, with distinct routing algorithms in each pathway (Jaseemuddin et al., 2006). A source routing protocol is created that permits a source to discover several routing pathways to a similar destination and then divide the traffic between these pathways using a specific method (Figure 3.10) (Nandiraju et al., 2009).

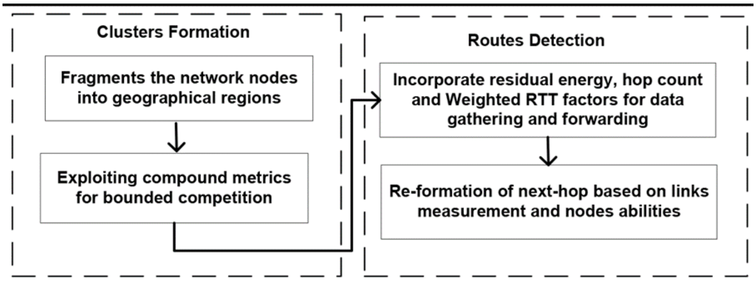


Figure 3.10. Structure of dependability aware routing.

Source: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0222009.

3.7.5. Steadiness-Aware Routing

This class of routing algorithms uses a unique system design to increase steadiness. Mesh routers are typically static in WMNs, with certain mesh nodes, like pathways, linked to wired networks. To increase routing steadiness, a routing algorithm might choose certain wired connections or even more static nodes in a routing pathway (Amir et al., 2007). Throughout this area of routing algorithms, just initial findings have been reported, and additional investigation is required.

3.7.6. Scalable Routing

A sustainable routing algorithm must be developed for a massive scale WMN. The scalability of a routing algorithm may be improved in a variety of ways. Geographic routing and hierarchical routing are the most fascinating options, as they are orthogonal to routing algorithms in all of the types previously mentioned (Xu et al., 2003). On the other hand, we may use geographic routing and hierarchical routing to combine routing methods from other types. For ad hoc networks, various hierarchical routing algorithms have been devised, however, some are accessible for WMNs, but few initial findings have been published (Lee et al., 2006; Lang, 2007). Geographical routing methods for ad hoc networks in depth are investigated. They may not be simply used to WMNs if they are modified to take into account the unique characteristics of WMNs. Geographic routing offers the benefit of not depending on the design of the network, but it is essential to include routing parameters like connection quality instead of only hop data, particularly for WMNs (Lee et al., 2005). We would explore several routing methods relevant to WMNs, particularly multichannel routing algorithms, based on the aforementioned classification. Furthermore, because multichannel routing systems have unique issues, there is a distinct chapter devoted to the multichannel routing algorithm. It must also be mentioned that certain routing algorithms may be divided into several classes due to diverse efficiency objectives being addressed, however, they would be described in the class that fulfills the primary goal for the sake of presenting simplification.

3.8. HOP-COUNT BASED ROUTING ALGORITHMS

3.8.1. Light Client Management Routing (LCMR) Algorithm

In this scenario, assertive paths among reactive routes and mesh routers across mesh routers and consumer routers make up the end-to-end routing pathway from an origin to a destination consumer. Hop-count is often utilized as a routing parameter to identify the optimal path from the first client to the second. The mesh routers that serve consumers take better care of routing; therefore, LCMR does not need routing capability in consumers. Mesh routers must therefore keep two tables: first for local customers' MAC and IP addresses, and the second for distant customers' IP addresses and also the IP addresses of distant mesh routers connected with distance consumers. Once a local consumer wants to build up a routing pathway to a distant consumer, its connected mesh router may use these two tables to figure out which distant mesh router is in charge of transmitting traffic to the distant consumer. The mesh routers may then use proactive routing and a hop-count measure to put up a routing pathway between them based on this data (Figure 3.11) (Raja et al., 2019).

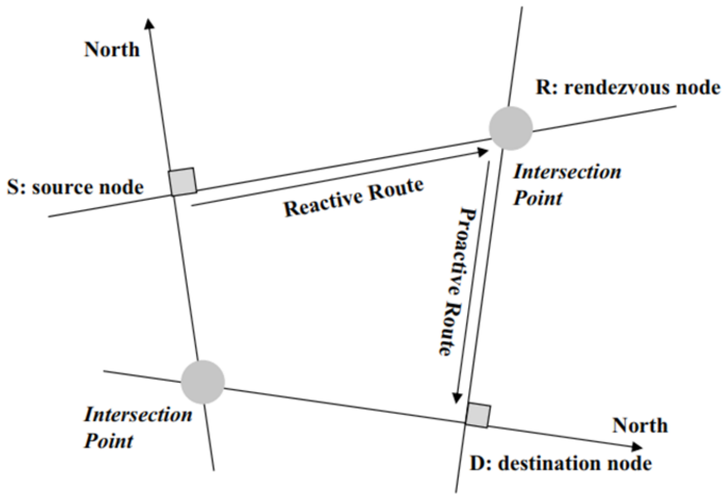


Figure 3.11. An easy system procedure of a routing pathway in ORR.

Source: https://onlinelibrary.wiley.com/doi/10.1002/9780470059616.ch4.

Because all consumers' IP addresses must be gathered and kept at every mesh router, LCMR has a significant cost for managing the two tables on every mesh router.

3.8.2. Orthogonal Rendezvous Routing (ORR) Protocol

That protocol is designed for mesh nodes that can communicate in both directions (Cheng et al., 2008). Every node may specify the orientations of its peers concerning its own local North. ORR may minimize state data for routing by depending on this knowledge, and route creation does not require flooding. ORR does not require the precise position of nodes, unlike geographic routing. It is dependent on the notion that 2 orthogonal lines in two-dimensional Euclidean space may cross at least twice with the other group of 2 orthogonal lines if the centers of the 2 groups of orthogonal lines are distinct. A source node transmits path discovery in orthogonal directions, whereas a target node transmits path propagation in orthogonal ways to build routing routes. As a result, at least one intersection point, referred to as the target destination, receives both path discovery and path propagation signals. A routing pathway is formed among the origin and target in this manner. Furthermore, the pathway from the origin to the target destination is reactive, whereas the pathway from the target destination is a reactive pathway and the residual pathway to the target is a proactive pathway (Owczarek and Zwierzykowski, 2013). We understand that ORR vastly overstates WMNs because of its methodology. First of all, a node's orientation must be flexibly set. Secondly, the network is not a two-dimensional space. If a three-dimensional space is taken into account, the ORR hypothesis cannot be true. Third, if the density of the node is large or geometry changes often, ORR cannot operate. Lastly, the hop count is used to select the routing pathway. Furthermore, other measures, like the quality of connection, may be used to improve the ORR (Lata and Kang, 2020).

3.8.3. HEAT Algorithm

Multicast routing algorithm known as HEAT is based on the concept of a temp field (Baumann et al., 2007). HEAT treats a WMN's nodes like a temp field. The temp is the hottest at the entrances. The temp of a non-entrances node is defined by the number of hops between it and the entrances, as well as the resilience of the routing pathway between it and the gateways. If the temperatures of all nodes have been calculated using this approach, packets from any node to the pathways may easily obey the following protocol: the node sends the packets to its maximum-temperature peer, who then repeats the procedure till the packets reach the pathways. As a result, any non-doorway node may simply pathway packets to doorways without having to establish a routing pathway between specific (origin-target) pairs. It must be emphasized, although, that the multicast technique is based on the premise that WMN traffic simply requires to be routed among doorways and non-doorways; multicast routing is not allowed in other circumstances. Furthermore, how to take into account further routing parameters into HEAT is also an open issue (Greengard and Strain, 1990; Xie et al., 2008).

REFERENCES

1. Abdulla, A. E., Nishiyama, H., & Kato, N., (2012). Extending the lifetime of wireless sensor networks: A hybrid routing algorithm. *Computer Communications*, *35*(9), 1056–1063.
2. Ahmed, E., Shiraz, M., & Gani, A., (2013). Spectrum-aware distributed channel assignment for cognitive radio wireless mesh networks. *Malaysian Journal of Computer Science*, *26*(3), 232–250.
3. Akyildiz, I. F., Lee, W. Y., Vuran, M. C., & Mohanty, S., (2006). NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks*, *50*(13), 2127–2159.
4. Akyildiz, I. F., Pelech, J. I., & Yener, B., (2001). A virtual topology-based routing protocol for multihop dynamic wireless networks. *Wireless Networks*, *7*(4), 413–424.
5. Akyildiz, I. F., Pompili, D., & Melodia, T., (2005). Underwater acoustic sensor networks: Research challenges. *Ad Hoc Networks*, *3*(3), 257–279.
6. Akyildiz, I. F., Wang, X., & Wang, W., (2005). Wireless mesh networks: A survey. *Computer Networks*, *47*(4), 445–487.
7. Al-Karaki, J. N., Al-Mashaqbeh, G. A., & Bataineh, S., (2017). Routing protocols in wireless mesh networks: A survey. *International Journal of Information and Communication Technology*, *11*(4), 445–495.
8. Alzamzami, O., & Mahgoub, I., (2018). Fuzzy logic-based geographic routing for urban vehicular networks using link quality and achievable throughput estimations. *IEEE Transactions on Intelligent Transportation Systems*, *20*(6), 2289–2300.
9. Amir, Y., Danilov, C., Musaloiu-Elefteri, R., & Rivera, N., (2007). An inter-domain routing protocol for multi-homed wireless mesh networks. In: *2007 IEEE International Symposium on a World of Wireless, Mobile, and Multimedia Networks* (Vol. 6, pp. 1–10).
10. Amish, P., & Vaghela, V. B., (2016). Detection and prevention of wormhole attack in wireless sensor network using AOMDV protocol. *Procedia Computer Science*, *79*, 700–707.
11. Asgarieh, Y., & Lin, B., (2019). Smart-hop arbitration request propagation: Avoiding quadratic arbitration complexity and false negatives in SMART NoCs. *ACM Transactions on Design Automation of Electronic Systems (TODAES)*, *24*(6), 1–25.

12. Azzoug, Y., & Boukra, A., (2021). Bio-inspired VANET routing optimization: An overview. *Artificial Intelligence Review*, *54*(2), 1005–1062.
13. Babber, K., & Randhawa, R., (2017). A cross-layer optimization framework for energy efficiency in wireless sensor networks. *Wireless Sensor Network*, *9*(06), 189.
14. Barz, C., Fuchs, C., Kirchhoff, J., Niewiejska, J., & Rogge, H., (2015). OLSRv2 for community networks: Using directional airtime metric with external radios. *Computer Networks*, *93*, 324–341.
15. Baumann, R., Heimlicher, S., Lenders, V., & May, M., (2007). HEAT: Scalable routing in wireless mesh networks using temperature fields. In: *2007 IEEE International Symposium on a World of Wireless, Mobile, and Multimedia Networks* (Vol. 7, pp. 1–9).
16. Baumann, R., Heimlicher, S., Strasser, M., & Weibel, A., (2007). A survey on routing metrics. *TIK Report*, *262*, 1–53.
17. Belding-Royer, E. M., (2003). Multi-level hierarchies for scalable ad hoc routing. *Wireless Networks*, *9*(5), 461–478.
18. Biswas, S., & Morris, R., (2005). ExOR: Opportunistic multi-hop routing for wireless networks. In: *Proceedings of the 2005 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications* (Vol. 10, No. 7, pp. 133–144).
19. Çepelioğullar, Ö., Mutlu, İ., Yaman, S., & Haykiri-Acma, H., (2018). Activation energy prediction of biomass wastes based on different neural network topologies. *Fuel*, *220*, 535–545.
20. Cheng, B. N., Yuksel, M., & Kalyanaraman, S., (2008). Orthogonal rendezvous routing protocol for wireless mesh networks. *IEEE/ACM Transactions on Networking*, *17*(2), 542–555.
21. Čičić, T., (2008). On basic properties of fault-tolerant multi-topology routing. *Computer Networks*, *52*(18), 3325–3341.
22. Conti, M., & Giordano, S., (2014). Mobile ad hoc networking: Milestones, challenges, and new research directions. *IEEE Communications Magazine*, *52*(1), 85–96.
23. Conti, M., Boldrini, C., Kanhere, S. S., Mingozzi, E., Pagani, E., Ruiz, P. M., & Younis, M., (2015). From MANET to people-centric networking: Milestones and open research challenges. *Computer Communications*, *71*, 1–21.

24. Cummins, J. M., Breen, T. M., Harrison, K. L., Shaw, J. M., Wilson, L. M., & Hennessey, J. F., (1986). A formula for scoring human embryo growth rates in in vitro fertilization: its value in predicting pregnancy and in comparison, with visual estimates of embryo quality. *Journal of In Vitro Fertilization and Embryo Transfer*, *3*(5), 284–295.
25. Dai, M., Li, C., Que, X., & Cui, Y., (2019). DGBA: Delay-guaranteed bitrate adaptation for mobile broadcaster in interactive live video streaming. *Journal of Physics: Conference Series*, *1176*(2), 022041.
26. De Couto, D. S., Aguayo, D., Bicket, J., & Morris, R., (2003). A high-throughput path metric for multi-hop wireless routing. In: *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking* (Vol. 87, pp. 134–146).
27. Desai, U. B., Jain, B. N., & Merchant, S. N., (2007). Wireless sensor networks: Technology roadmap. In: *Workshop on Wireless Sensor Networks at IITB on April* (Vol. 20, No. 6, p. 207).
28. Dhamdhere, A., Luckie, M., Huffaker, B., Claffy, K. C., Elmokashfi, A., & Aben, E., (2012). Measuring the deployment of IPv6: Topology, routing, and performance. In: *Proceedings of the 2012 Internet Measurement Conference* (Vol. 7, No. 6, pp. 537–550).
29. Di Francesco, M., Anastasi, G., Conti, M., Das, S. K., & Neri, V., (2011). Reliability and energy-efficiency in IEEE 802.15. 4/ZigBee sensor networks: An adaptive and cross-layer approach. *IEEE Journal on Selected Areas in Communications*, *29*(8), 1508–1524.
30. Draves, R., Padhye, J., & Zill, B., (2004). Comparison of routing metrics for static multi-hop wireless networks. *ACM SIGCOMM Computer Communication Review*, *34*(4), 133–144.
31. Draves, R., Padhye, J., & Zill, B., (2004). Routing in multi-radio, multi-hop wireless mesh networks. In: *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking* (Vol. 35, No. 7, pp. 114–128).
32. Du, S., Khan, A., PalChaudhuri, S., Post, A., Saha, A. K., Druschel, P., & Riedi, R., (2008). Safari: A self-organizing, hierarchical architecture for scalable ad hoc networking. *Ad Hoc Networks*, *6*(4), 485–507.
33. Fan, W., & Machemehl, R. B., (2006). Optimal transit route network design problem with variable transit demand: Genetic algorithm approach. *Journal of Transportation Engineering*, *132*(1), 40–51.

34. Fortz, B., Rexford, J., & Thorup, M., (2002). Traffic engineering with traditional IP routing protocols. *IEEE Communications Magazine*, *40*(10), 118–124.
35. Ghannay, S., Gammar, S. M., Filali, F., & Kamoun, F., (2012). Multi-radio multi-channel routing metrics in IEEE 802.11 s based wireless mesh networks. *Annals of Telecommunications-Annales des Télécommunications*, *67*(5), 215–226.
36. Greengard, L., & Strain, J., (1990). A fast algorithm for the evaluation of heat potentials. *Communications on Pure and Applied Mathematics*, *43*(8), 949–963.
37. Gungor, V. C., & Lambert, F. C., (2006). A survey on communication networks for electric system automation. *Computer Networks*, *50*(7), 877–897.
38. Gupta, L., Jain, R., & Vaszkun, G., (2015). Survey of important issues in UAV communication networks. *IEEE Communications Surveys & Tutorials*, *18*(2), 1123–1152.
39. Iannone, L., & Fdida, S., (2005). Meshdv: A distance vector mobility-tolerant routing protocol for wireless mesh networks. In: *IEEE ICPS Workshop on Multi-Hop Ad Hoc Networks: From Theory to Reality* (Vol. 5, pp. 103–110).
40. Ishmael, J., Bury, S., Pezaros, D., & Race, N., (2008). Deploying rural community wireless mesh networks. *IEEE Internet Computing*, *12*(4), 22–29.
41. Jakllari, G., Eidenbenz, S., Hengartner, N., Krishnamurthy, S. V., & Faloutsos, M., (2011). Link positions matter: A noncommutative routing metric for wireless mesh networks. *IEEE Transactions on Mobile Computing*, *11*(1), 61–72.
42. Jaseemuddin, M., Esmailpour, A., Alwan, A., & Bazan, O., (2006). Integrated routing system for wireless mesh networks. In: *2006 Canadian Conference on Electrical and Computer Engineering* (Vol. 70, No. 6, pp. 1003–1007).
43. Jevtic, N. J., & Malnar, M. Z., (2019). Novel ETX-based metrics for overhead reduction in dynamic ad hoc networks. *IEEE Access*, *7*, 116490–116504.
44. Ji, Y., Wang, X., Zhang, S., Gu, R., Guo, T., & Ge, Z., (2016). Dual-layer efficiency enhancement for future passive optical network. *Science China Information Sciences*, *59*(2), 1–13.

45. Jia, S., Luckie, M., Huffaker, B., Elmokashfi, A., Aben, E., Claffy, K., & Dhamdhere, A., (2019). Tracking the deployment of IPv6: Topology, routing, and performance. *Computer Networks*, *165*, 106947.
46. Johnson, D., & Hancke, G., (2009). Comparison of two routing metrics in OLSR on a grid-based mesh network. *Ad Hoc Networks*, *7*(2), 374–387.
47. Jun, J., & Sichitiu, M. L., (2008). MRP: Wireless mesh networks routing protocol. *Computer Communications*, *31*(7), 1413–1435.
48. Karbaschi, G., & Fladenmuller, A., (2005). A link-quality and congestion-aware cross layer metric for multi-hop wireless routing. In: *IEEE International Conference on Mobile Ad Hoc and Sensor Systems Conference* (Vol. 9, No. 8, p. 7).
49. Kartal, F., & Özveren, U., (2020). A deep learning approach for prediction of syngas lower heating value from CFB gasifier in Aspen plus®. *Energy*, *209*, 118457.
50. Keshav, S., (1995). A control-theoretic approach to flow control. *ACM SIGCOMM Computer Communication Review*, *25*(1), 188–201.
51. Khan, A. S., Qahar, A., Fauzi, A. H., & Javed, Y., (2018). Using green and emerging technology. *Asian Journal of Information Technology*, *17*(1), 23–51.
52. Khan, M. A., Khan, I. U., Safi, A., & Quershi, I. M., (2018). Dynamic routing in flying ad-hoc networks using topology-based routing protocols. *Drones*, *2*(3), 27.
53. Kim, K. H., & Shin, K. G., (2006). On accurate measurement of link quality in multi-hop wireless mesh networks. In: *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking* (Vol. 8, No. 4, pp. 38–49).
54. Koksal, C. E., & Balakrishnan, H., (2006). Quality-aware routing metrics for time-varying wireless mesh networks. *IEEE Journal on Selected Areas in Communications*, *24*(11), 1984–1994.
55. Krioukov, D., Claffy, K. C., Fall, K., & Brady, A., (2007). On compact routing for the internet. *ACM SIGCOMM Computer Communication Review*, *37*(3), 41–52.
56. Kumar, S., Singh, B., & Sharma, S., (2013). Soft computing framework for routing in wireless mesh networks: an integrated cost function approach. *arXiv preprint arXiv*, 4(7), 1307–3011.

57. Lang, S. B., (2007). Guide to the literature of piezoelectricity and pyroelectricity. 27. *Ferroelectrics*, *350*(1), 124–239.
58. Lata, A. A., & Kang, M., (2020). A survey on the evolution of opportunistic routing with asynchronous duty-cycled MAC in wireless sensor networks. *Sensors*, *20*(15), 4112.
59. Lavanya, G., & Jeyakumar, A. E., (2011). An enhanced secured dynamic source routing protocol for MANETS. *International Journal of Soft Computing and Engineering*, *10*, 135–140.
60. Lee, K. K., Kim, S. H., Choi, Y. S., & Park, H. S., (2006). A mesh routing protocol using cluster label in the ZigBee network. In: *2006 IEEE International Conference on Mobile Ad Hoc and Sensor Systems* (Vol. 10, pp. 801–806).
61. Lee, S., Bhattacharjee, B., & Banerjee, S., (2005). Efficient geographic routing in multihop wireless networks. In: *Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing* (Vol. 9, pp. 230–241).
62. Lenders, V., May, M., & Plattner, B., (2008). Density-based anycast: A robust routing strategy for wireless ad hoc networks. *IEEE/ACM Transactions on Networking*, *16*(4), 852–863.
63. Li, H., Cheng, Y., Zhou, C., & Zhuang, W., (2012). Routing metrics for minimizing end-to-end delay in multiradio multichannel wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, *24*(11), 2293–2303.
64. Lim, A. O., Wang, X., Kado, Y., & Zhang, B., (2008). A hybrid centralized routing protocol for 802.11 s WMNs. *Mobile Networks and Applications*, *13*(1), 117–131.
65. Lin, D., Moh, T. S., & Moh, M., (2006). A delay-bounded multi-channel routing protocol for wireless mesh networks using multiple token rings: extended summary. In: *Proceedings. 2006 31st IEEE Conference on Local Computer Networks* (Vol. 70, No. 9, pp. 845–847).
66. Liu, X., Zhang, X., Lu, R., Xue, P., Xu, D., & Zhou, H., (2011). Low-dimensional nanostructures fabricated from bis (dioxaborine) carbazole derivatives as fluorescent chemosensors for detecting organic amine vapors. *Journal of Materials Chemistry*, *21*(24), 8756–8765.
67. Lui, K. S., Nahrstedt, K., & Chen, S., (2004). Routing with topology aggregation in delay-bandwidth sensitive networks. *IEEE/ACM Transactions on Networking*, *12*(1), 17–29.

68. Ma, L., & Denko, M. K., (2007). A routing metric for load-balancing in wireless mesh networks. In: *21st International Conference on Advanced Information Networking and Applications Workshops* (Vol. 2, pp. 409–414).
69. Ma, L., Zhang, Q., Xiong, Y., & Zhu, W., (2005). Interference aware metric for dense multi-hop wireless networks. In: *IEEE International Conference on Communications* (Vol. 2, pp. 1261–1265).
70. Malnar, M. Z., & Neskovic, N. J., (2011). An analysis of performances of multi-channel routing protocol based on different link quality metrics. In: *2011 10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services* (Vol. 2, pp. 737–740).
71. Malnar, M., Neskovic, N., & Neskovic, A., (2014). Novel power-based routing metrics for multi-channel multi-interface wireless mesh networks. *Wireless Networks*, *20*(1), 41–51.
72. McQuillan, J., Richer, I., & Rosen, E., (1980). The new routing algorithm for the ARPANET. *IEEE Transactions on Communications*, *28*(5), 711–719.
73. Medvidovic, N., & Taylor, R. N., (2000). A classification and comparison framework for software architecture description languages. *IEEE Transactions on Software Engineering*, *26*(1), 70–93.
74. Menon, V. G., Jogi Priya, P. M., & Joe Prathap, P. M., (2013). Analyzing the behavior and performance of greedy perimeter stateless routing protocol in highly dynamic mobile ad hoc networks. *Life Science Journal*, *10*(2), 1601–1605.
75. Modiano, E., & Narula-Tam, A., (2001). Survivable routing of logical topologies in WDM networks. In: *Proceedings IEEE INFOCOM 2001. Conference on Computer Communications. 20th Annual Joint Conference of the IEEE Computer and Communications Society* (Vol. 1, pp. 348–357).
76. Nandiraju, D. S., Nandiraju, N. S., & Agrawal, D. P., (2009). Adaptive state-based multi-radio multi-channel multi-path routing in wireless mesh networks. *Pervasive and Mobile Computing*, *5*(1), 93–109.
77. Nandiraju, N., Nandiraju, D., Santhanam, L., He, B., Wang, J., & Agrawal, D. P., (2007). Wireless mesh networks: Current challenges and future directions of web-in-the-sky. *IEEE Wireless Communications*, *14*(4), 79–89.

78. Ni, X., Lan, K. C., & Malaney, R., (2008). On the performance of expected transmission count (ETX) for wireless mesh networks. In: *Proceedings of the 3rd International Conference on Performance Evaluation Methodologies and Tools*, *8*(3), 1–10.

79. Nikkhah, M., & Guérin, R., (2015). Migrating the internet to IPv6: An exploration of the when and why. *IEEE/ACM Transactions on Networking*, *24*(4), 2291–2304.

80. Owczarek, P., & Zwierzykowski, P., (2013). Routing protocols in wireless mesh networks: A comparison and classification. *Information System Architecture and Technology*, *3*, 85–95.

81. Ozonoh, M., Oboirien, B. O., & Daramola, M. O., (2020). Optimization of process variables during torrefaction of coal/biomass/waste tyre blends: Application of artificial neural network & response surface methodology. *Biomass and Bioenergy*, *143*, 105808.

82. Ozonoh, M., Oboirien, B. O., Higginson, A., & Daramola, M. O., (2020). Performance evaluation of gasification system efficiency using artificial neural network. *Renewable Energy*, *145*, 2253–2270.

83. Ozonoh, M., Oboirien, B. O., Higginson, A., & Daramola, M. O., (2020). Dataset from estimation of gasification system efficiency using artificial neural network technique. *Chemical Data Collections*, *25*, 100321.

84. Pandey, D. S., Das, S., Pan, I., Leahy, J. J., & Kwapinski, W., (2016). Artificial neural network-based modelling approach for municipal solid waste gasification in a fluidized bed reactor. *Waste Management*, *58*, 202–213.

85. Park, Y., Shim, J., Jeong, S., Yi, G. R., Chae, H., Bae, J. W., & Pang, C., (2017). Microtopography-guided conductive patterns of liquid-driven graphene nanoplatelet networks for stretchable and skin-conformal sensor array. *Advanced Materials*, *29*(21), 1606453.

86. Pfrommer, J., Warrington, J., Schildbach, G., & Morari, M., (2014). Dynamic vehicle redistribution and online price incentives in shared mobility systems. *IEEE Transactions on Intelligent Transportation Systems*, *15*(4), 1567–1578.

87. Pirzada, A. A., Portmann, M., & Indulska, J., (2006). Evaluation of multi-radio extensions to AODV for wireless mesh networks. In: *Proceedings of the 4th ACM International Workshop on Mobility Management and Wireless Access* (Vol. 5, No. 8, pp. 45–51).

88. Qu, Y., Ng, B., & Seah, W., (2016). A survey of routing and channel assignment in multi-channel multi-radio WMNs. *Journal of Network and Computer Applications*, *65*, 120–130.

89. Raja, G. P., & Mangai, S. J. C. C., (2019). Firefly load balancing based energy optimized routing for multimedia data delivery in wireless mesh network. *Cluster Computing*, *22*(5), 12077–12090.

90. Rasool, T., Srivastava, V. C., & Khan, M. N. S., (2018). Utilization of a waste biomass, walnut shells, to produce bio-products via pyrolysis: Investigation using ISO-conversional and neural network methods. *Biomass Conversion and Biorefinery*, *8*(3), 647–657.

91. Rault, T., Bouabdallah, A., & Challal, Y., (2014). Energy efficiency in wireless sensor networks: A top-down survey. *Computer Networks*, *67*, 104–122.

92. Razzaque, M. A., Alam, M. M., Mamun-Or-Rashid, M., & Hong, C. S., (2008). Multi-constrained QoS geographic routing for heterogeneous traffic in sensor networks. *IEICE Transactions on Communications*, *91*(8), 2589–2601.

93. Reina, D. G., Tawfik, H., & Toral, S. L., (2018). Multi-subpopulation evolutionary algorithms for coverage deployment of UAV-networks. *Ad Hoc Networks*, *68*, 16–32.

94. Ros, J., & Tsai, W. K., (2010). A lexicographic optimization framework to the flow control problem. *IEEE Transactions on Information Theory*, *56*(6), 2875–2886.

95. Sanmartin, P., Rojas, A., Fernandez, L., Avila, K., Jabba, D., & Valle, S., (2018). Sigma routing metric for RPL protocol. *Sensors*, *18*(4), 1277.

96. Shen, Q., Fang, X., & Shan, Y., (2006). An integrated metrics based extended dynamic source routing protocol for wireless mesh networks. In: *2006 International Conference on Communications, Circuits, and Systems* (Vol. 3, pp. 1457–1461).

97. Silva, A. V. S., Torquato, L. D. M., & Cruz, G., (2019). Potential application of fish scales as feedstock in thermochemical processes for the clean energy generation. *Waste Management*, *100*, 91–100.

98. Sivanesan, K., & Mazzarese, D., (2006). Cooperative techniques in the IEEE 802 wireless standards: Opportunities and challenges. *Cooperation in Wireless Networks: Principles and Applications*, 497–514.

99. Song, W., & Fang, X., (2006). Routing with congestion control and load balancing in wireless mesh networks. In: *2006 6th International Conference on ITS Telecommunications* (Vol. 6, pp. 719–724).
100. Tang, J., Xue, G., & Zhang, W., (2005). Interference-aware topology control and QoS routing in multi-channel wireless mesh networks. In: *Proceedings of the 6th ACM international Symposium on Mobile ad Hoc Networking and Computing* (Vol. 9, pp. 68–77).
101. Thaalbi, M., & Tabbane, N., (2012). An enhanced geographical routing protocol for wireless mesh networks, 802.11s. *International Journal of Computer Applications*, *51*(10).
102. Tilston, M., Arnott, R. W., Rennie, C. D., & Long, B., (2015). The influence of grain size on the velocity and sediment concentration profiles and depositional record of turbidity currents. *Geology*, *43*(9), 839–842.
103. Tran, D. T., Iosifidis, A., & Gabbouj, M., (2018). Improving efficiency in convolutional neural networks with multilinear filters. *Neural Networks*, *105*, 328–339.
104. Wang, L. Q., & Chen, Z. S., (2013). Experimental studies on H_2-rich gas production by Co-gasification of coal and biomass in an intermittent fluidized bed reactor. *Advanced Materials Research*, *724*, 1127–1131.
105. Wehbi, B., Mallouli, W., & Cavalli, A., (2006). Light client management protocol for wireless mesh networks. In: *7th International Conference on Mobile Data Management* (Vol. 8, pp. 123–123).
106. Wendel, H., & Bisch, P. M., (1984). On the interplay of microscopic order and macroscopic properties in solvent-saturated lipid films. *Surfactants, Micelles, Microemulsions, and Liquid Crystals*, 113–126.
107. Wu, K., & Harms, J., (2001). Performance study of a multipath routing method for wireless mobile ad hoc networks. In: *MASCOTS 2001, Proceedings Ninth International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems* (Vol. 6, No. 3, pp. 99–107).
108. Wu, T. Y., & Chan, H. L., (2010). Integrate airtime metric and geocast over P2P-based VoD streaming cache. *Journal of Applied Science and Engineering*, *13*(1), 99–106.
109. Xie, G. N., Sundén, B., & Wang, Q. W., (2008). Optimization of compact heat exchangers by a genetic algorithm. *Applied Thermal Engineering*, *28*(8–9), 895–906.

110. Xing, J., Luo, K., Wang, H., & Fan, J., (2019). Estimating biomass major chemical constituents from ultimate analysis using a random forest model. *Bioresource Technology*, *288*, 121541.
111. Xing, J., Wang, H., Luo, K., Wang, S., Bai, Y., & Fan, J., (2019). Predictive single-step kinetic model of biomass devolatilization for CFD applications: A comparison study of empirical correlations (EC), artificial neural networks (ANN) and random forest (RF). *Renewable Energy*, *136*, 104–114.
112. Xu, K., Hong, X., & Gerla, M., (2003). Landmark routing in ad hoc networks with mobile backbones. *Journal of Parallel and Distributed Computing*, *63*(2), 110–122.
113. Xu, L., Collier, R., & O'Hare, G. M., (2017). A survey of clustering techniques in WSNs and consideration of the challenges of applying such to 5G IoT scenarios. *IEEE Internet of Things Journal*, *4*(5), 1229–1249.
114. Yang, Y., Wang, J., & Kravets, R., (2006). Load-balanced routing for mesh networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, *10*(4), 3–5.
115. Youssef, M., Ibrahim, M., Abdelatif, M., Chen, L., & Vasilakos, A. V., (2013). Routing metrics of cognitive radio networks: A survey. *IEEE Communications Surveys & Tutorials*, *16*(1), 92–109.
116. Yuan, Y., Yang, H., Wong, S. H., Lu, S., & Arbaugh, W., (2005). ROMER: Resilient opportunistic mesh routing for wireless mesh networks. In: *IEEE Workshop on Wireless Mesh Networks* (Vol. 12, pp. 6–19).
117. Zhang, L., Deering, S., Estrin, D., Shenker, S., & Zappala, D., (1993). RSVP: A new resource reservation protocol. *IEEE Network*, *7*(5), 8–18.
118. Zhong, W., Xu, L., Liu, X., Zhu, Q., & Zhou, J., (2019). Adaptive beam design for UAV network with uniform plane array. *Physical Communication*, *34*, 58–65.
119. Zhou, W., Zhang, D., & Qiao, D., (2006). Comparative study of routing metrics for multi-radio multi-channel wireless networks. In: *IEEE Wireless Communications and Networking Conference* (Vol. 1, pp. 270–275).
120. Zhu, B., Liao, J., He, Y., & Li, Z., (2013). Incompatibility between WCETT route metric and flooding control of AODV in wireless mesh networks. In: *Proceedings of the 2nd International Conference on Green Communications and Networks* (Vol. 3, pp. 619–626).

Chapter 4

Physical Layer Technique

CONTENTS

4.1. INTRODUCTION

As the circuit design for wireless communications, digital signal processing algorithms, RF technologies, and communication theories grow rapidly the physical layer (PHY) techniques developed quickly. In three directions these techniques primarily focus on: improving software controllability and reconfigurability of radios, in a wireless environment refining error resilience capability, and growing transmission rate.

Several high-speed physical methods have been developed to improve the volume of wireless networks. For instance, OFDM (orthogonal frequency division multiplexing) has meaningly improved the speed of IEEE 802.11 from 11 Mbps to 54 Mbps. Ultra-wideband (UWB) approaches can produce a substantially greater transmission rate. UWB, on the other hand, is limited to short-range applications such as wireless personal area networks (WPANs). Other physical mechanisms, like the MIMO (multiple-input multiple-output) method, are required if a transmission speed as high as UWB is sought in a broader area network like WMANs or WLANs. Multiple antenna systems (Shiu et al., 2011; Wu et al., 2018) are being employed for wireless communication to boost capacity and counteract the effects of co-channel interference (CCI), delay-spread, and fading. It should be emphasized that while a new PHY approach is being developed to boost the transmission rate, spectrum efficacy must be preserved as high as feasible (Figure 4.1).

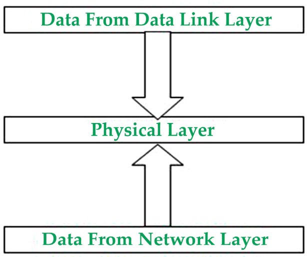


Figure 4.1. Schematic illustration of different network layers.

Source: https://www.geeksforgeeks.org/physical-layer-in-osi-model/.

Several channel coding techniques have been developed to improve error resilience. A fixed channel coding technique is inefficient because channel conditions vary. As a result, a channel coding system that is adaptable is required. Coding schemes must be changed as channel situations vary in IEEE 802.11a and 3G cellular networks (Schaefer and Boche, 2014).

PHY methods are advanced in the third direction so that they can be measured through software. Wireless communications benefit greatly from this feature. PHY approaches, for example, can be adjusted adaptively in response to changing environmental situations, allowing the development and research cycle to be drastically shortened, reconfigured the radios. The finite wireless spectrum can better be utilized when reasoning radios are addressed (Wang et al., 2019).

Advanced strategies in all three dimensions are presented in this chapter. Techniques with high potential for WMNs are examined in particular. Coding, multi-antenna systems and adaptive modulation, link variation techniques, software radios, and other similar technologies are examples. The IEEE 802.11n PHY is explored to show how diverse PHY approaches can be combined into a similar system (Mukherjee et al., 2014).

4.2. ADAPTIVE CODING/MODULATION AND LINK ADAPTATION

Generally, there are two types of variation in a wireless network:

- **Large Scale Variations:** These are caused by shadow fading, which is caused by variable path loss among receiver and transmitter and variable alteration of the mean value of path loss.
- **Small Scale Variations:** These are produced by multipath propagation, which causes significant swings in received signal strength over a short time or travel distance. Frequency selective fading can occur in a broadband network as a result of these fast fluctuations.

If the same modulation and coding scheme is utilized the whole time due to differences in channel quality, the BER (bit error rate) in a channel differs dramatically, reducing channel size and degrading the working of upper layer procedures (Liu et al., 2016).

Adaptive channel coding and modulation, which is used in several wireless networks like IEEE 802.11 wireless LANs and 3G cellular networks, is a good way to overcome this problem. The numerous modulation algorithms and channel coding of IEEE 802.11a, for example, are presented in Table 4.1.

Table 4.1. IEEE 802.11a Channel Coding and Modulation

Modu-lation	**Coded Bits per OFDM Symbol**	**Data Bits per OFDM Symbol**	**Trans-mission Rate**	**Coding Rate (Mbps)**
BPSK	48	36	9	3/4
BPSK	48	24	6	1/2
QPSK	96	72	18	3/4
QPSK	96	48	12	1/2
16 QAM	192	144	36	3/4
16 QAM	192	96	24	1/2
64 QAM	288	216	54	3/4
64 QAM	288	192	48	2/3

Adaptive error resilience can be supplied via the link variation using adaptive modulation and channel coding (Ahmed et al., 2003; Jiao et al., 2019). The transmission rate of IEEE 802.11a is substantially higher if link adaptation is used, as demonstrated in Figure 4.2. Link adaption is commonly employed in IEEE 802.11 wireless LANs because of this benefit (Tang et al., 2001).

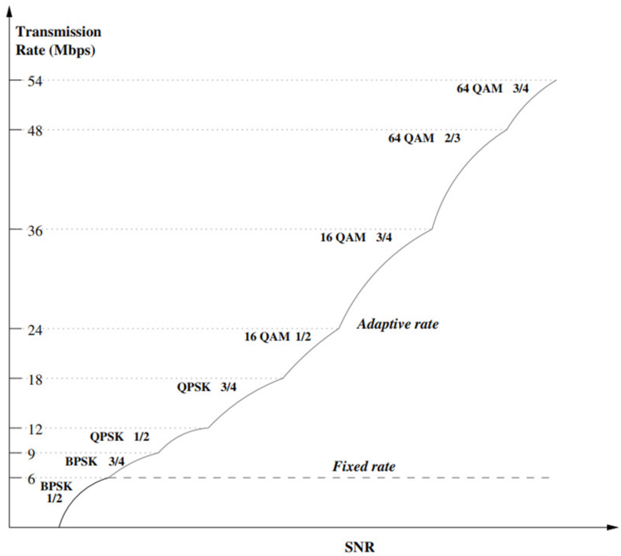


Figure 4.2. Adaptive transmission rate.

Source: https://onlinelibrary.wiley.com/doi/10.1002/9780470059616.ch2.

Link adaptation is based on the simple principle of altering transmission parameters to take benefit of current channel situations. When link flexibility is sought, however, numerous possible concerns must be considered:

- **Impact on the MAC Protocol:** To take advantage of the PHY's adaptive channel coding/modulation capacity, a MAC layer algorithm must be built. At the MAC layer, to put it another way, link adaptation is typically done. For example, in IEEE 802.11 MAC, a rate control algorithm must be built to adaptively pick the appropriate transmission rate based on channel conditions (Tang et al., 2001). Link adaptation, on the other hand, on the design of a MAC procedure may have an impact. The changing transmission period of a packet, for example, renders any techniques based on packet count ineffective. In addition, when evaluating the performance of a MAC procedure, it is vital to account for the fluctuating transmission rate caused by link adaptation.
- **Selection of Channel State Information (CSI) and its Availability:** A channel quality indicator is known as CSI. Signal-to-noise ratio (SNR), BER, and carrier-to-interference ratio (CIR) are examples of CSI at the PHY, and packet error rate (PER) at the link layer. However, in a wireless network, some of them may be difficult to measure. However, for link adaptation, a single form of CSI may not be adequate. A link adaptation algorithm, for example, cannot take CIR or SNR as a single input from the PHY in a frequency-selective fading environment because CIR or SNR alone does not sufficiently characterize channel quality (Ahmed and Yanikomeroglu, 2009).
- **Dimensions of Transmission Parameters:** In few wireless networks, transmission characteristics other than modulation and coding levels must be adjusted. Space, spreading features, frequency, time, and power levels other parameters may all need to be adjusted. The connection adaption algorithms might be somewhat sophisticated due to the multiple dimensions of transmission parameters. Link adaptation procedures for the MIMO (multiple input multiple outputs) systems, for example, are still a research problem. Moreover, with several options, link adaptation is typically a cross-layer optimization problem including the MAC and PHYs (Ahmed et al., 2004).

4.3. DIRECTIONAL ANTENNAS AND MULTI-ANTENNA SYSTEMS

Reflect uses numerous antennas or directional communications on a similar communication node to increase PHY performance in a wireless setting. It is worth noting that a multi-antenna communication system includes both baseband and RF components.

4.3.1. Directional Antenna

In a wireless network, directional antennas allow for reception and directional transmission, which has various advantages.

4.3.1.1. Better Spatial Reuse Efficiency

Because reception and transmission are both directional, the reuse of channels does not require spatial departure, which enhances channel spatial reuse efficacy dramatically. This function aids in the expansion of network capacity (Zhou et al., 2010).

4.3.1.2. Lower Interference

Interference and collisions between various nodes are reduced using reception and directional transmission. This function boosts a network's throughput and QoS.

4.3.1.3. Less Energy Consumption for the Same Network Capacity

A directional antenna requires low spread power than an Omni-directional antenna for a similar transmission range. As a result, for a similar transmission rate, a node will yield less interference to other nodes. This characteristic not only enhances network capacity but also improves energy efficiency (Baliga et al., 2009).

4.3.1.4. Better Security

Eavesdropping is substantially more tough with the directed transmission, which improves network security at the PHY. The following approaches can be used to create directional antennas.

4.3.1.5. Steerable Antenna

Each node has one antenna pointing in a certain direction in this example. The antenna must be electronically or physically steerable to point in the appropriate direction at the precise time when networking with other nodes (Friis and Feldman, 1937). It is not always a decent solution for WMNs since the process of changing the direction of a dirigible antenna is measured than ad hoc networking requirements.

4.3.1.6. Antenna Switching

Each node contains several antennas pointing in various directions. If a node needs to interact with nodes in various directions, it must change antennas. This method is fast enough to meet the requirement for ad hoc networking. Since the coverage and direction of a directional antenna are constantly secure, the disadvantage of this sort of directional antenna is its lack of flexibility (Gou et al., 2011).

4.3.1.7. Beamforming

There are many antennas on each node. Using beamforming techniques, however, the key beam of antennas is directed in the direction required by upper-layer procedures, while nulls are preserved in undesirable directions. The direction of the primary beam can be changed to the right with precise graininess using signal processing algorithms (Figure 4.3).

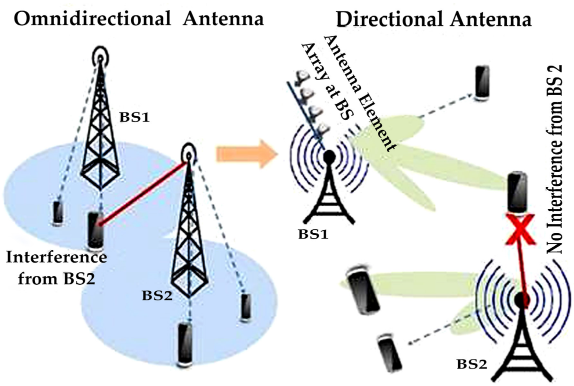


Figure 4.3. Beam forming directional antennas.

Source: https://www.researchgate.net/figure/Beam-Forming-Directional-Antennas-103_fig4_325935862.

WMNs can benefit more from directional antennas than single-hop networking like cellular networks or wireless LANs. The reason for this is that a node in a WMN experiences substantially higher resource rivalry with other nodes due to the mesh architecture and multihop, and so directional antennas can meaningly lessen this type of resource battle. However, because of the mesh topology, governing directional antennas in WMNs is more difficult. Higher layer protocols, particularly routing and MAC protocols, must be modified to fully exploit the benefits of directional antennas. Several MAC protocols have supported that directional antenna be considered in ad hoc networks (Cox et al., 1987; Chen et al., 2002). Nevertheless, only a few MAC protocols designed exclusively for WMNs have been developed. Furthermore, a single-protocol-layer solution might not be effective (Van and Buckley, 1988).

It is usual in WMNs for nodes to have numerous radios. When these radios are used in conjunction with directional antennas, the capacity of the network can be boosted even more. Nevertheless, in order to make use of these advantages, new procedures must be devised.

4.3.2. Antenna Diversity and Smart Antenna

Node A is considered to have M antennas for broadcast and for the reception it has N antennas in Figure 4.4, whereas node B has K antennas for broadcast, and for the reception, it has L antennas. Various multiple-antenna systems come from different values of M, N, K, and L.

4.3.2.1. Single Transmitting Antenna Multiple Receiving Antennas

If a multi-antenna system has several antennas in the receiver but only one antenna in the transmitter, techniques like adaptive/smart antennas and antenna diversity can be employed. They have been proposed for single-hop point-to-multipoint cellular networks (Jeng et al., 1998).

The concept of antenna diversity depends on the circumstance that signals established from unrelated antennas fade at different rates. As a result, there is a good chance that the receiver will pick up at least one good signal. Different types of diversity are commonly used to produce antenna uncorrelation (Figure 4.4) (Gu et al., 2015):

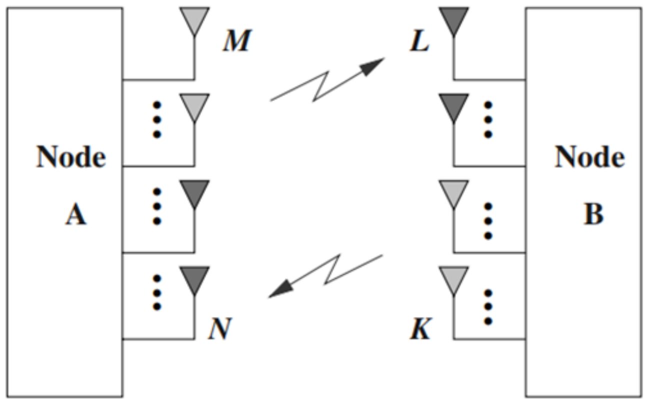


Figure 4.4. Multiple-antenna systems.

Source: https://ieeexplore.ieee.org/book/8039718.

- **Space Diversity:** This is the most basic form of antenna diversity, which is produced by separating antennas by a set number of wavelengths. When antennas are all in the same place, spatial diversity is lost.
- **Polarization Diversity:** Because polarization diversity allows antennas to be in the same position, it has become an additional appealing method of attaining antenna diversity. It is, however, a more difficult technique than spatial variety.
- **Pattern Diversity:** Even though the antennas are in the same place, variety can be obtained by altering the emission patterns at separate sites. Pattern diversity, on the other hand, is more intricate than space diversity.
- Signal processing is required, in order to utilize diversity. The most common techniques are explained as follows (Bhobe and Perini, 2001).
- **Switch Diversity:** The best-signal-receiving antenna is chosen. BER, Signal strength, and other signal quality parameters can be used.
- **Equal Gain Combining:** An equal improvement combination method can be employed to co-phase signals and put them collected to improve switch diversity performance.

- **Maximum Ratio Combining (MRC):** Before integrating signals, MRC uses SNRs to weigh them. In the presence of noise, it is the best method.

It should be mentioned that depending on the kind of antenna diversity employed, different signal processing techniques must be applied. Switch diversity, for example, may not be useful if polarization or pattern diversity are employed, therefore MRC is the finest option (Perini, 2006).

When there is a lot of interference, diversity dispensation unaided is not enough to provide high-quality signals. Smart antennas or adaptive antenna array processing are employed to tailor the antenna beamform to improve the intended signals while canceling out the intrusive signals. The key antenna beam, for example, can be shaped to emphasize wanted signals, with ciphers of beam pattern fixed in places where interference signals occur (Boukalov and Haggman, 2000).

Adaptive antenna dispensation typically implies that a training sequence can obtain some of the required signal information. The bulks of a space-time receiver are then changed to reduce the MMSE (minimum mean square error) among received and known signals. The optimal merging of incoming signals is done by the space-time receiver. It is the same as the MRC method for antenna diversity when there is no interference. Some systems for detecting the directions of incoming signals have been projected so far. The desired signals are merged based on these directives. These systems may be beneficial in literature, but they are not feasible in practice because signal arrivals may be distributed in too many directions (Basha et al., 2012).

For diverse networks, the precise approaches to smart antennas or antenna diversity vary a lot. Smart antenna approaches are difficult to deploy in a network without a training order, such as IEEE 802.11a/g or 802.11b based wireless networks. The optimal combination can be done in TDMA-based networks like TDMA or IEEE 802.16 cellular networks rely on the training sequence inside a time-space. Because a rake receiver now provides diversity in CDMA networks, the smart antenna will primarily improve action by lowering multiple access interference (MAI) or CCI. Furthermore, because there are no leading interferers in a CDMA network, it is difficult to cancel interfering signals using antenna arrays with limited degrees of freedom. Because no weight tracking or calculation is required with these fixed antenna beams, the multi-antenna system is simple (Shaukat et al., 2009). Because several mesh routers are prepared with these technologies, smart antennas and antenna diversity are commonly adopted in WMNs.

However, more research into their performance in WMNs is required. In a multihop mesh topology, the first difficulty is its complexity. A completely flexible smart antenna system is only employed in cellular network base stations because of its complexity and cost, and ongoing research and development efforts are still needed to integrate a completely adaptive smart antenna system in a movable terminal. Due to the significantly more intricate network architecture of WMNs, this problem gets even worse. The 2nd challenge is how to retain or improve the effectiveness of these systems when traditional point-to-multipoint connections are no longer available (Thompson et al., 1996; Basha et al., 2011).

4.3.2.2. Multiple Transmitting Antennas Single Receiving Antenna

If the transmitter has multiple antennas and the receiver has only one antenna, It is difficult to implement smart antenna techniques or antenna diversity when N = 1, L = 1, and either K > 1 or M > 1. As the receiver has just a single antenna, the transmitter antennas should be constructed properly so that the incoming signals at the receiver maintain the smart antenna or antenna diversity performance gain. One crucial prerequisite for achieving this goal is that channel state information (CSI) be provided at the transmitter. Schemes like for example, presume that CSI is completely understood (Telatar, 1999).

Nevertheless, in most cases, only a portion of the channel's state is known. Because of channel fluctuations in time, this information can be extracted from a contrary link for a TDD (time division duplex) system, but it is still insufficient to reflect forward link CSI. The CSI of backward and forward connections is independent in a frequency division duplex (FDD) system. As a result, in a multi-antenna system with a single reception antenna and numerous transmitter antennas, antenna diversity or smart antenna must be developed without CSI. This method may be feasible, but its effectiveness is limited.

Space-time coding (STC) is a general strategy for achieving variation in this setting. Rather than the transmitter, this approach seeks to grow the performance increase at the receiver. Nevertheless, for the receiver to the advantage of the received signal, the transmitter must use a coding scheme that divides the processing of signals on antennas into separate symbol periods (Farrokhi et al., 2001; Tu and Pottie, 2002). When a receiver receives these coded signals, it can use an algorithm like MLD to merge them (Maximum Likelihood Detection). The following is an explanation of a simple STC system revealed by Alamouti (1998). One receiving antenna and two transmitting antennas are used in this arrangement. The signals are concurrently sent at the two antennas, in the subsequent symbol period n + 1, where signifies the composite conjugate operation. At the receiver, when these signals arrive, methods like MLD can combine and distinguish them. With one transmitting antenna and two receiving antennas, the STC provides a similar diversity gain as the MRC in this example. The disadvantage is that if the overall transmit power is constant, each antenna loses 3 dB of power. STC, on the other hand, is a potential strategy for attaining second-order diversity without expanding bandwidth (Bahceci et al., 2003).

Up to the present time, smearing the smart antenna method to a multi-antenna system with a single antenna at the reception and many antennas at the transmitter has proven to be extremely difficult. There haven't been any viable schemes projected up till now.

4.3.2.3. MIMO

MIMO is a multiple-antenna system in which several antennas are utilized at both the receiver and the transmitter, i.e., M > 1, L > 1 or K > 1, N > 1. Because a MIMO can use both multiplexing and diversity of concurrent data streams, it has the potential to enhance system capacity by three times or more (Larsson et al., 2014). MIMO is currently supported by IEEE 802.11n (Donzelli et al., 2007).

Based on spatially detached antennas, MIMO systems can be developed. Compressed antennas are required for specific applications; hence MIMO systems must be built on vector antennas (Goldsmith et al., 2003). These vector antennas are made up of pieces that are co-located, such as two dipoles and one loop. Vector antennas are an example of design variety. MIMO with co-located antennas can also boost capacity by a factor of several. However, it still has a lesser capacity and BER than MIMO systems with spatially detached antennas.

A MIMO system can be categorized into three variants based on where MIMO signal handing out is done: transmitter processing only, receiver processing alone, or both transmitter and receiver processing MIMO systems.

- **Transmitter Processing Only MIMO:** The receiver in this form of MIMO system does not require MIMO signal processing, but rather numerous front ends. As a result, multiple independent front tops along with detached data streams are connected to the antennas at the receiver. Then these data streams are combined into a single data stream, resulting in a significantly advanced data rate than a single antenna system (Vishwanath et al., 2003). Because at the receiver no MIMO dispensation is required, the transmitter contains a MIMO processing technique for the intended signals to have a sufficient signal-to-interference-noise ratio (SINR). The transmit MMSE, transmit zero-forcing system, and the sieve bank scheme is some of the available algorithms. Beforehand signals are sent in separate antennas, the transmitter uses an intrusion pre-eliminating step in the transmit zero-forcing method. Therefore, at the receiver when these signals are conventional, there is strong enough to be identified (Gesbert et al., 2003). The sieve bank system seeks to optimize the least SINR of a subchannel among all subchannels. When the MMSE is transmitted, the transmitter weights are optimized so that the mean square error among the estimated and transmitted symbols is as small as possible. Despite the availability of many receiving antennas, no current technique can deliver receiver diversity without MIMO processing at the receiver.

- **Receiver Processing Only MIMO:** In this situation, the transmitter is easy, as each antenna's transmitter can be regular. A stream of single data is demultiplexed obsessed by multiple sub streams that are moderated and sent at diverse transmitters before being transferred. It is worth noting that the symbols for each transmitter must be drawn in a specific fashion from the gathering such that the total radiated power from all transmitters remains reliable (Banerjee et al., 2001; Loyka, 2001).
- **Space-Time Coding (STC):** A basic coding procedure is used to encode the data stream crosswise wholly transmitting antennas in this scheme. Complicated decoding algorithms are required at the receiver to decode the received signals. As a result, the receiver bears the brunt of MIMO processing complexity.
- When there are only two antennas, a basic decoding system like the Alamouti (1998) scheme can be utilized. Nevertheless, there are currently no common and operative decoding techniques obtainable. As a result, low-complexity space-time codes must be developed to attain sufficient performance.

- **V-BLAST:** In V-BLAST, just standard receivers are required. As a result, its primary goal is to eliminate data sub stream interference caused by other data sub streams. V-BLAST accomplishes this simply by employing a reiterative optimal joining and interference cancellation approach. First, all received data sub streams are subjected to optimum combining. When the greatest sub stream is discovered, its signal is negated out. The remaining sub streams are then subjected to optimum combining to determine the best sub stream. This operation is repetitive till all sub streams have been obtained and are ready to be detected (Loyka and Gagnon, 2004).
- **MLD:** For MIMO the MLD is an ideal receiver that recognizes multiple data streams concurrently. As compared to V-BLAST it has higher intricacy. When a similar number of transmitting and receiving antennas are used, however, MLD for MIMO constantly outperforms V-BLAST in terms of performance (e.g., BER).
- **Both Transmitter and Receiver MIMO Processing:** Because MIMO processing is used at both the receiver and transmitter, it is fair to predict that these MIMO systems will perform substantially better than the earlier two MIMO systems. It is also true that these MIMO systems are extremely complex. They are not suitable for use with mobile terminals or mesh clients. SVD (Singular value decomposition). Chuah et al. (2002) has proven to be the most common method for doing both receiver and transmitter MIMO processing. To create independent channels, it diagonalizes MIMO stations, which can subsequently be used with water filling systems to increase general system capacity.

Because of the varying complexity constraints on the receiver and transmitter, the above MIMO systems are preferred by different application scenarios. Because we wish to consent to the very sophisticated dispensation to base stations instead of mobile terminals, transmitter processing-only MIMO systems are favored in the downlink and receiver dispensation only MIMO systems are favored in the uplink in a cellular system (Shiu et al., 2000).

We do not have this option in a mobile ad hoc network because all nodes have similar dispensation capabilities. Though, the condition in WMNs is improved than it is in cellular and mobile ad hoc networks (MANETs). Due to mesh routers' high dispensation capabilities, all forms of MIMO systems can be used for communications between them. We can use transmitter-processing-only MIMO on links among mesh clients and mesh routers, and receiver-processing-only MIMO on links among mesh routers and mesh clients for communications among mesh clients and mesh routers. This shows how WMNs have a benefit over other wireless networks. Nevertheless, a technique to allow mesh clients and mesh routers to operate diverse MIMO systems in a similar network must be devised (Telatar, 1999).

This appears to be simple for mesh clients, but it is more challenging for mesh routers because a mesh router must allow communication with both other mesh routers and mesh clients. The problem is simplified if different radios are used for mesh client and mesh backbone communications, and separately radio is prepared with a separate MIMO system.

When mesh routers only have a single radio, innovative MIMO schemes must be developed so that the downlink to mesh clients is transmitter-processing-only MIMO, the downlink and uplink among mesh routers can be in the least form of MIMO scheme and the uplink from mesh clients is receiver-processing-only MIMO (Figure 4.5) (Moustakas et al., 2003).

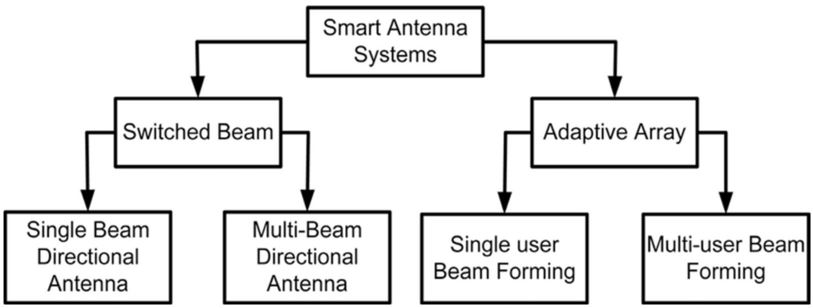


Figure 4.5. Types of smart antenna.

Source: https://www.researchgate.net/figure/Types-of-Smart-Antenna_fig1_317993287.

4.4. COOPERATIVE DIVERSITY AND COOPERATIVE COMMUNICATIONS

Because of the lack of additional antennas in several application situations, multi-antenna systems are not feasible. There are various motives why a network node should only have one antenna:

- **Cost and Size of a Node:** Size and cost must be kept to a minimum in networking devices, such as cellphones (Tao et al., 2012). It will be difficult to achieve this target if multi-antenna systems are used.
- **Not Enough Separation on the Same Node:** An effective multi-antenna system requires a distance of greater than half a wavelength among antennas on a similar node (Sadek et al., 2006). When using a frequency of 5.0 GHz, such as that used in IEEE 802.11a, a spacing of several millimeters is required. When using an IEEE 802.11g frequency, the separation distance is substantially greater. A mobile terminal, a mesh router, or mesh client cannot readily meet such a demand.

  Customer supportive diversity has been projected in wireless networks to investigate the diversity gain without multi-antenna systems (Scaglione et al., 2006; Letaief and Zhang, 2009).

As soon as Node A directs a signal to Node B, added node, such as Node C, hears it and communicates it to Node B; thus, at Node B the signal collected is the total of signals through 2 dissimilar but self-governing disappearing paths, such as via supportive communications spatial diversity has been attained among different nodes. As a result, in order for network nodes with one antenna to attain diversity, every node should perform two tasks: spread data and act as a supportive agent relaying data to other nodes (Hong et al., 2007).

Through this simple idea of getting user supportive diversity, in this mechanism, we can have several exciting difficulties:

- **The Tradeoff of Power:** Because a single signal must be delivered to 2 separate nodes, sending data from base to final destination requires more power. However, at every node, while using diversity, the transmit power can be lower than when using the non-cooperative method. As a result, a power distribution algorithm must be developed to ensure that minimal transmit power is needed to sustain user supportive diversity.
- **The Tradeoff of the Transmission Rate:** A node in supportive communication, must both relay and transmit data from other nodes. As a result, the rate of transmission is lowered. Nevertheless, the coding rates of the channel might be greater because of diversity, which raises the transmission rate. As a result, it is unlikely that the real transmission rate will be decreased. We must analyze the

tradeoff among diversity and reduced transmission probability in order to keep the transmission rate as high as possible (Hong et al., 2007).

- **Interference:** Because a similar signal is delivered multiple times in the network, interference may grow with cooperative diversity. Diversity, on the other hand, may lower the transmit power level, compensating for the enlarged interference (Waqas et al., 2013).
- **Cooperation Assignment Scheme:** This is concerned with locating other supportive nodes for every node in order to attain variety. Cooperation assignment may be a simple process in a network with a one-hop infrastructure. Cooperation assignment in a multihop dispersed network, like WMNs, is more difficult since it must consider numerous elements like fairness across nodes, power, interference, and diversity gain.
- **New Requirements on Network Nodes:** Though supportive communications can provide variety; techniques are still required to extract innovative data through multiplexed signals. This necessitates more processing power on both the receiver and the transmitter. It is possible that the functioning of supportive communications will necessitate hardware variations in every node.

As a result, three methods are required to achieve user cooperative diversity. The first procedure seeks to allocate supportive nodes to every node in the most effective way possible, achieving the greatest tradeoff among power and diversity, interference, and transmission. The second approach, given an ideal assignment process, provides a way for relaying signals in supportive nodes. The third process looks for unique data among the multiplexed data of initially sent and relayed signals (Sadek et al., 2006).

Numerous systems up till now have been planned for transmitting signals in supportive nodes (Su et al., 2008; Waqas et al., 2013):

- **Amplify and Forward Scheme:** The partner node increases the established signal with sound and sends the boosted signal in this technique (Su et al., 2005). The disadvantage of this system is that it necessitates complex circuitry to increase and forward analog signals. This technique has the advantage of not requiring inter-user channel state data and allowing typical channel estimates to be employed.

- **Decode and Forward Scheme:** A node in this architecture decodes the signal before retransmitting it. Zafar et al. (2012) provide an example of this technique. The disadvantage of this technique is that a node may be unable to identify its partner's signal appropriately. Relaying signals will spread faults in this instance. Another disadvantage of this system is that the receiver requires inter-user channel data.
- **Coded Cooperation:** The data stream of each node is divided into blocks using a channel coding technique (Ibrahim and Liu, 2009). The codeword is divided into two parts, each of N1 and N2 bits. When a node delivers data, it sends N1 bits of the codeword first, then decodes data from its partner node. If decoding is effective, the node estimates its partner node's second part before transmitting the N2 bits. Else, it will send a second part on its own. Inter-user channel data is not required for this technique. Because cooperation is restricted, the receiver must know whether or not the transmit nodes have cooperated. Liu et al. (2017) also discuss other coded cooperative techniques.
- **Selection Relay:** A threshold test should be taken to evade error spread, before relaying signals. When it is fulfilled, the relay is completed. Else, a node desires to come in a noncooperative method. In this manner, coded support is also a kind of selection relay scheme.

From multiplexed signals, several approaches for detecting innovative signals have been presented. The most basic strategy is for relayed and original signals to arrive at separate times. Nevertheless, these, TDMA techniques may not be effective, and time slot distribution may be challenging. Unique signals with CDMA and multiplex relayed could be employed. Furthermore, frequency division multiple access is an option. Regardless of the multiple access technique employed, procedures must be designed to recognize original signals as accurately as feasible (Saeed et al., 2019).

In wireless networks, user-supportive communications are beneficial thus far. But, duo to 3 motives, the research is still in its early stages. To begin with, most current methods have merely considered how cooperative nodes can efficiently transfer data. New methods are needed to assign cooperative nodes to improve interference, transmission rate, and power. Second, no workable remedy has yet been suggested.

Most current systems, for example, assume that essential control is provided, that basic network architecture is taken into account, and that just simple multiple access is measured. Existing techniques are inadequate for WMNs due to these restrictions. Third, several present schemes depend on inter-user channel station data that may or may not be provided. It is necessary to build new systems that do not or just partially rely on such information.

Nonetheless, user supportive diversity is a capable technology since a) it can allow low-cost network nodes to contain a diversity of antenna, thereby growing general network capacity; b) it can act in combination with multi-antenna schemes to improve network act, and c) it can assist in collision resolution deprived of applying the reservation-based MAC procedure (Roberts et al., 2006).

4.5. MULTICHANNEL SYSTEMS

Multiple channels in the frequency spectrum of a wireless radio are commonly presented in WMNs. If WMNs depend on IEEE 802.11g, for instance, there are more than 3 nonoverlapping channels presented. This figure is higher when IEEE 802.11a is taken into account. The network performance and capacity can be considerably boosted when numerous channels are employed for simultaneous communication. A multichannel scheme can be constructed in a variety of means (Figure 4.6).

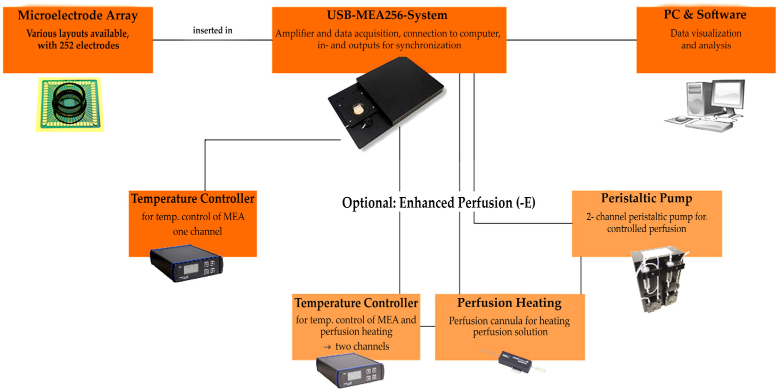


Figure 4.6. The USB-MEA 256-system consisting of only four components: The microelectrode array, the recording device itself, the data acquisition computer, and the temperature controller.

Source: https://bronjo.com/multi-channel-systems-usb-mea-256-system/.

- **Single Transceiver on a Single Radio:** In this situation, a wireless radio can labor on multiple stations, at a time but it can simply work on one. As a result, on the time axis, the radio must alter channels to meet the requirements of upper-layer protocols like routing schemes or MAC. A multichannel scheme relied on these radios is inexpensive, nevertheless, it can decrease interference and hence boost capacity. The difficulties are two-fold. Primary, the speed of channel switching must be rapid; else, channel switching above will be extremely high. Second, the MAC procedure must decide the optimal time to switch stations (Kirkeby et al., 1998).
- **Multiple transceivers on a single radio**: Simultaneous broadcasts in separate channels can be reinforced by a manifold transceiver radio. In cellular networks, a base station with several transceivers has been introduced. Nevertheless, due to system complications and cost considerations, a wireless radio with many transceivers has not yet matured as a WMN technology. Even though IEEE 802.11 chipsets with numerous transceivers are now presented, their price is still prohibitively high (Kollmann et al., 2012).

  The network can have more volume than a network with only one transceiver radios since several transceivers are on the same radio. Nevertheless, because there are many transceivers, the routing or MAC protocol's channel distribution procedures must decide multiple channels at once. Although switching of the channel is not continuously essential, it is necessary because a node's required channels may alter in order to reduce total network disturbance.

  Thus, quick channel switching speed is desirable in many applications. If a radio contains 3 transceivers, it can meet multichannel communications deprived of channel switching in some simple application scenarios, like a home network.
- **Multiple Radios each with Multiple Transceivers:** On a network node, this example shows a multichannel system with the most degrees of freedom for channel distribution. As a result, both network capacity and cost may be at their peak.

  It is also feasible for all four kinds of nodes, or a combination of them, to exist in a similar WMN. The MAC procedure, along with the routing procedure, must be flexible enough to adapt to all eventualities to adapt to this generic example. Procedures that presume a fixed channel on a node, for example, are not relevant (Tartakovsky et al., 2003).

4.6. ADVANCED RADIO TECHNOLOGIES

Reconfigurable radios, software radios, and cognitive radios are just a few of the advanced radio technologies that can help with WMN research and development. The development period of a new protocol can be substantially shorter in some circumstances, such as with reconfigurable radios or software radios. Protocols can also be established over reconfigurable radios for an accurate product deprived of having to change the chipset design (Novak and Waterhouse, 2013).

Furthermore, networking procedures can reconfigure wireless radios to get the best possible routine. Other times, radios must be vigorously altered in order to apprehend radios like cognitive radios or frequency agile radios. As a result, modern radio technologies are required to construct WMNs.

4.6.1. Frequency Agile Radios and Cognitive Radios

In a wireless network Frequency bandwidth is a valuable source. Nevertheless, several of the currently available frequency bands are underutilized. According to FCC measurements, over 70% of the due spectrum is not used (Minden et al., 2007). Furthermore, wireless communication spectrum tenancy can last anywhere from milliseconds to hours (79). As a result, there is still plenty of spectrum offered.

Moreover, the complication of a high-scale ad hoc network exceeds human planning, making conventional static frequency planning impractical (Dudley et al., 2014). Frequency agile or cognitive radios are being advanced to vigorously capture the unoccupied spectrum to attain significantly improved spectrum use and viable frequency planning. The FCC has known the technique's bright future and is working to bring it to fruition (Figure 4.7).

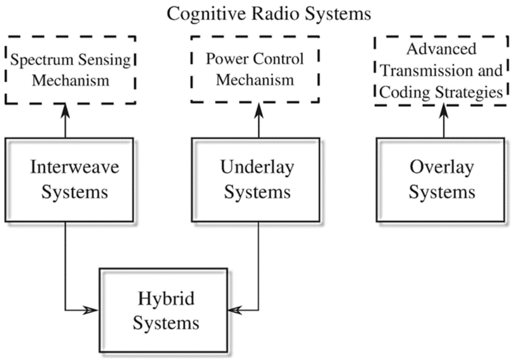


Figure 4.7. Illustration of cognitive radio systems.

Source: https://link.springer.com/referenceworkentry/10.1007%2F978-981-10-1394-2_4.

4.6.2. Reconfigurable Radios and Software Radios

Reconfigurable radios have been around for a long time. Now, several wireless radios can be changed to some extent. Few commercially obtainable IEEE 802.11 radios, for example, through modifying the PHY register configurations and MAC can be reprogrammed. The radios can be reconfigured to work firmly as required by upper-layer protocols by resetting these registers. Software radio, in which programmability occurs in all apparatuses of a radio, such as channel modulations, channel access modes, and programmable RF bands, is the ultimate aim of reconfigurable radio (Hou et al., 2008).

Though testbeds are already accessible, software radio is not yet an established approach. Software radios, on the other hand, will be a crucial approach for wireless communications in the long run. They have the potential to be one of the most practical platforms for cognitive radios (Muhammad et al., 2005).

Advanced physical methods like coding and adaptive modulation, MIMO systems, regulators for directional and smart antennas, multichannel radios, and so on are easier to implement with software radios. They also allow MAC and higher-layer protocols to be reconfigured, allowing them to be better developed in conjunction with the PHY. Software radios can also be used to create frequency agile or cognitive radios (Dejonghe et al., 2007).

4.7. INTEGRATING DIFFERENT ADVANCED TECHNIQUES: IEEE 802.11N

The progressive PHY approaches described in earlier segments have been useful to real-world wireless networks like IEEE 802.16, 802.15, and 802.11. The high throughput (HT) PHY of 802.11 such that IEEE 802.11n is described in this part to demonstrate how several advanced approaches are merged into the similar PHY of 802.11. Advanced coding functions and adaptive modulation, MIMO, and multichannel operations are all trained in combination with OFDM.

This example does not offer supportive communication methods since 802.11n does not contain this ability for two reasons: 1) While 802.11n is being quantified, supportive communications methods are not yet mature enough for everyday usage; 2) while 802.11n is being quantified, supportive communications methods are not yet mature enough for everyday usage (Figure 4.8) (Mueck et al., 2010).

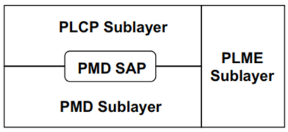


Figure 4.8. Protocol reference model of IEEE 802.11n physical layer.

Source: https://slideplayer.com/slide/7715025/.

4.7.1. Protocol Reference Model of the Physical Layer (PHY)

The 802.11n PHY protocol design tails a general approach, as depicted in Figure 4.8. In the data plane, the PHY is divided into two sublayers: at the top is the PLCP (physical layer convergence procedure) and the at the bottom PMD (physical medium dependent). The physical layer management entity (PLME) in the management plane is in charge of these sublayers (Stojmenovic et al., 2005).

4.7.2. PLCP Sublayer

The PLCP sublayer permits the MAC layer to rely on the PMD sublayer as little as possible. Its main role is to alter a physical layer service data unit (PSDU) to a PLCP protocol data unit (PPDU) or the other way around. This process includes the majority of 802.11n PHY functions.

4.7.3. PMD Sublayer

The PMD sublayer defines the service primitives for SAP (the service access point) among the PMD and PLCP sublayers, as well as the PMD transmitter and receiver specifications. The following specifications are provided for a PMD receiver:

- **Receiver Minimum Input Sensitivity:** This compassion is calculated using a PER of < 10% for a 4,096-byte packet service data unit (PSDU). The receiver minimum input sensitivity is similarly rated reliant on because the coding and modulation scheme varies with the rate. Multiple antennas may be utilized in a MIMO system; hence this sensitivity is indicated per receive antenna (Nicholl et al., 2007).
- **Adjacent Channel Rejection:** The power differential between the interfering signal and the desired signal is called adjacent channel rejection, and it is determined by placing the desired signal level 3 dB above the receiver minimum input sensitivity and then raising the interfering signal until a PER of 10% is attained. In the 5 GHz band, the interfering and desirable signals are separated by 20 MHz, while in the 2.4 GHz range, they are separated by 25 MHz. The main frequencies of the intrusive and intended signals are detached by 40 MHz in 802.11n channels with 40 MHz channels.
- **Non-Adjacent-Channel Rejection:** Non-adjacent channel rejection is measured using a scheme similar to that used for neighboring channel rejection. For 20 MHz channels, the center frequencies of the interfering and intended signals must be detached by 40 MHz, and for 40 MHz channels, by 80 MHz.
- **Receiver Maximum Input Level:** The receiver extreme input level is provided for any baseband variation so that PER does not go past 10%.
- **Clear Channel Assessment (CCA) Sensitivity:** A signal level is specified in CCA sensitivity at which a receiver is demanding. For a valid 802.11n signal the receiver will go demanding if it surpasses the minimum receiver minimum input sensitivity between all modulation and coding methods. CCA must keep the receiver busy for any additional signals that are 20 dB over the smallest receiver minimum sensitivity. Even though the node senses that the channel is clean as per the CCA edge, interfering

may still occur, according to CCA requirements. Lowering the CCA threshold, on the other hand, is not a viable option (Hu et al., 2017).

- **Received Channel Power Indicator:** This pointer monitors the established RF power over the data serving of the received frame given a channel.

  A packet sent with an RIFS (reduced interframe space) separation from the preceding packet must also be decoded by the PMD receiver. By splitting back-to-back transmissions from the same transmitter with a very tiny interframe space, RIFS tries to enhance efficiency. The 802.11n MIMO PHY takes just two seconds, but the slot time and short interframe space (SIFS) take nine and sixteen seconds.

To safeguard the suitable actions, a PMD transmitter must follow the following characteristics:

- Transmit spectrum mask.
- By using a specific station, given a frequency balance from the main frequency, the variety mask requires the PSD (power spectrum density) that a PMD transmitter must content. Because 802.11n can employ either a twenty or forty MHz channel, two spectrum masks are defined. The spectrum mask for a 20 MHz channel is shown in Figure 4.9, in which the PSD of each frequency is distinct about the signal's determined PSD, and the unit is dBr. Conformance to the spectrum mask is crucial for a PMD transmitter. If the PSD is less than that stated in the mask at a certain frequency, it signifies the PMD transmitter's spread power is less than authorized, which might result in a reduced transmission rate or coverage. If the PSD, in contrast, is more than the mask's stated value, it indicates that there are undesired discharges that may source needless interference (D'ambrosia, 2009).
- **Maximum Transmit Power:** Furthermore, the spectrum mask, as well as a PMD transmitter's maximum transmit power, must meet regulatory criteria in several regulatory areas.
- **Spectral Flatness:** The mean energy of the gatherings should be given for a subcarrier because the 802.11n PHY is constructed on the upper of OFDM. To safeguard spectral flatness, the mean

energy must be inside a minor deviation, such as in subcarriers 2 dB for the constellations 16 to 1 and +1 to +16.

- **Center Frequency and Symbol Clock Frequency Tolerance:** A specific range (e.g., ±20 ppm) of frequency oscillation must be tolerated by the PMD transmitter.
- **Packet Alignment:** The transmitter should release a PHY transmission end approve rude at the end of the final symbol of a packet to inform the MAC layer that the complete packet has been transferred over the air (D'ambrosia, 2009).

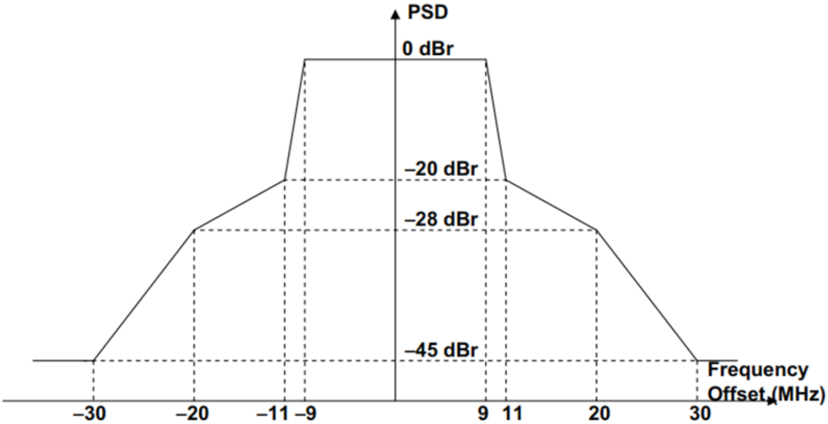


Figure 4.9. Transmit spectrum mask for a 20 MHz channel of 802.11n.

- **Modulation Accuracy:** To amount the modulation accurateness of the 802.11 PHYs, a variation accuracy-test technique provided in the 802.11n standard must be followed. The transmitter constellation error is a significant metric for modulation precision. This is an average of RMS (root mean square) errors above subcarriers, spatial streams, and OFDM frames. Because different variation algorithms are used for different transmission rates, the modulation accuracy is rate-dependent (Drolet and Duplessis, 2010).

The primitives of service are also described in the SAP among the PMD and PLCP sublayers to establish connections between peer nodes and sublayers.

4.7.4. PLME Sublayer

PHY units can contact several MIB (management information base) properties preserved by PLME. The MIB properties contain whole physical features, including MIMO operating parameters, power levels OFDM constraints, and. The 802.11n draught standard contains a complete list of MIB attributes (Lai et al., 2010).

REFERENCES

1. Ahmed, M. H., & Yanikomeroglu, H., (2009). Throughput fairness and efficiency of link adaptation techniques in wireless networks. *IET Communications*, *3*(7), 1227–1238.
2. Ahmed, M. H., Yanikomeroglu, H., & Mahmoud, S., (2003). Fairness enhancement of link adaptation techniques in wireless access networks. In: *2003 IEEE 58th Vehicular Technology Conference* (Vol. 3, pp. 1554–1557).
3. Ahmed, M. H., Yanikomeroglu, H., & Mahmoud, S., (2004). Fairness of link adaptation techniques in broadband wireless access networks. In: *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring* (Vol. 4, pp. 1944–1948).
4. Alamouti, S. M., (1998). A simple transmit diversity technique for wireless communications. *IEEE Journal on Selected Areas in Communications*, *16*(8), 1451–1458.
5. Andrei, M., & Nicolau, V., (2012). On image transmission in MIMO communication channels using Alamouti space-time codes. *The Annals of "Dunarea de Jos "University of Galati. Fascicle III, Electrotechnics, Electronics, Automatic Control, Informatics*, *35*(2), 13–18.
6. Bahceci, I., Duman, T. M., & Altunbasak, Y., (2003). Antenna selection for multiple-antenna transmission systems: Performance analysis and code construction. *IEEE Transactions on Information Theory*, *49*(10), 2669–2681.
7. Baliga, J., Ayre, R., Hinton, K., Sorin, W. V., & Tucker, R. S., (2009). Energy consumption in optical IP networks. *Journal of Lightwave Technology*, *27*(13), 2391–2403.
8. Banerjee, A. K., Mimo, M. L., & Vegas, W. V., (2001). Silica gel in organic synthesis. *Russian Chemical Reviews*, *70*(11), 971–990.
9. Basha, T. G., Aloysius, G., Rajakumar, B. R., Prasad, M. G., & Sridevi, P. V., (2012). A constructive smart antenna beam-forming technique with spatial diversity. *IET Microwaves, Antennas & Propagation*, *6*(7), 773–780.
10. Basha, T. G., Sridevi, P. V., & Prasad, M. G., (2011). Enhancement in gain and interference of smart antennas using two stage genetic algorithm by implementing it on beam forming. *International Journal of Electronics Engineering*, *3*(2), 265–269.

11. Bhobe, A. U., & Perini, P. L., (2001). An overview of smart antenna technology for wireless communication. In *2001 IEEE Aerospace Conference Proceedings, 2*, 2–875.
12. Boukalov, A. O., & Haggman, S. G., (2000). System aspects of smart-antenna technology in cellular wireless communications-an overview. *IEEE Transactions on Microwave Theory and Techniques*, *48*(6), 919–929.
13. Chen, J. C., Yao, K., & Hudson, R. E., (2002). Source localization and beamforming. *IEEE Signal Processing Magazine*, *19*(2), 30–39.
14. Chuah, C. N., Tse, D. N. C., Kahn, J. M., & Valenzuela, R. A., (2002). Capacity scaling in MIMO wireless systems under correlated fading. *IEEE Transactions on Information Theory*, *48*(3), 637–650.
15. Cox, H., Zeskind, R., & Owen, M., (1987). Robust adaptive beamforming. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, *35*(10), 1365–1376.
16. D'ambrosia, J., (2009). 40 gigabit ethernet and 100 gigabit ethernet: The development of a flexible architecture [Commentary]. *IEEE Communications Magazine*, *47*(3), 8–14.
17. Dejonghe, A., Bougard, B., Pollin, S., Craninckx, J., Bourdoux, A., Van der Perre, L., & Catthoor, F., (2007). Green reconfigurable radio systems. *IEEE Signal Processing Magazine*, *24*(3), 90–101.
18. Donzelli, E., Salvade, A., Mimo, P., Viganò, M., Morrone, M., Papagna, R., & Tredici, G., (2007). Mesenchymal stem cells cultured on a collagen scaffold: *In vitro* osteogenic differentiation. *Archives of Oral Biology*, *52*(1), 64–73.
19. Drolet, P., & Duplessis, L., (2010). 100G ethernet and OTU4 testing challenges: From the lab to the field. *IEEE Communications Magazine*, *48*(7), 78–82.
20. Dudley, S. M., Headley, W. C., Lichtman, M., Imana, E. Y., Ma, X., Abdelbar, M., & Reed, J. H., (2014). Practical issues for spectrum management with cognitive radios. *Proceedings of the IEEE*, *102*(3), 242–264.
21. Farrokhi, F. R., Foschini, G. J., Lozano, A., & Valenzuela, R. A., (2001). Link-optimal space-time processing with multiple transmit and receive antennas. *IEEE Communications Letters*, *5*(3), 85–87.

22. Foschini, G. J., & Gans, M. J., (1998). On limits of wireless communications in a fading environment when using multiple antennas. *Wireless Personal Communications*, *6*(3), 311–335.
23. Foschini, G. J., (1996). Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas. *Bell Labs Technical Journal*, *1*(2), 41–59.
24. Friis, H. T., & Feldman, C. B., (1937). A multiple unit steerable antenna for short-wave reception. *Proceedings of the Institute of Radio Engineers*, *25*(7), 841–917.
25. Gesbert, D., Shafi, M., Shiu, D. S., Smith, P. J., & Naguib, A., (2003). From theory to practice: An overview of MIMO space-time coded wireless systems. *IEEE Journal on Selected Areas in Communications*, *21*(3), 281–302.
26. Goldsmith, A., Jafar, S. A., Jindal, N., & Vishwanath, S., (2003). Capacity limits of MIMO channels. *IEEE Journal on Selected Areas in Communications*, *21*(5), 684–702.
27. Gou, T., Wang, C., & Jafar, S. A., (2011). Aiming perfectly in the dark-blind interference alignment through staggered antenna switching. *IEEE Transactions on Signal Processing*, *59*(6), 2734–2744.
28. Gu, C., Gao, S., Liu, H., Luo, Q., Loh, T. H., Sobhy, M., & Abd-Alhameed, R. A., (2015). Compact smart antenna with electronic beam-switching and reconfigurable polarizations. *IEEE Transactions on Antennas and Propagation*, *63*(12), 5325–5333.
29. Hassibi, B., & Hochwald, B. M., (2002). High-rate codes that are linear in space and time. *IEEE Transactions on Information Theory*, *48*(7), 1804–1824.
30. Hong, Y. W., Huang, W. J., Chiu, F. H., & Kuo, C. C. J., (2007). Cooperative communications in resource-constrained wireless networks. *IEEE Signal Processing Magazine*, *24*(3), 47–57.
31. Hou, Y. T., Shi, Y., & Sherali, H. D., (2008). Spectrum sharing for multi-hop networking with cognitive radios. *IEEE Journal on Selected Areas in Communications*, *26*(1), 146–155.
32. Hu, J., Chen, S., Zhao, L., Li, Y., Fang, J., Li, B., & Shi, Y., (2017). Link level performance comparison between LTE V2X and DSRC. *Journal of Communications and Information Networks*, *2*(2), 101–112.

33. Ibrahim, A. S., & Liu, K. R., (2009). Mitigating channel estimation error with timing synchronization tradeoff in cooperative communications. *IEEE Transactions on Signal Processing*, *58*(1), 337–348.
34. Jafarkhani, H., (2001). A quasi-orthogonal space-time block code. *IEEE Transactions on Communications*, *49*(1), 1–4.
35. Jeng, S. S., Okamoto, G. T., Xu, G., Lin, H. P., & Vogel, W. J., (1998). Experimental evaluation of smart antenna system performance for wireless communications. *IEEE Transactions on Antennas and Propagation*, *46*(6), 749–757.
36. Jiao, L., Wang, N., Wang, P., Alipour-Fanid, A., Tang, J., & Zeng, K., (2019). Physical layer key generation in 5G wireless networks. *IEEE Wireless Communications*, *26*(5), 48–54.
37. Kirkeby, O., Nelson, P. A., Hamada, H., & Orduna-Bustamante, F., (1998). Fast deconvolution of multichannel systems using regularization. *IEEE Transactions on Speech and Audio Processing*, *6*(2), 189–194.
38. Kobayashi, T., (2006). Measurements and characterization of ultra-wideband propagation channels in a passenger-car compartment. *IEICE Transactions on Fundamentals of Electronics, Communications, and Computer Sciences*, *89*(11), 3089–3094.
39. Kollmann, T., Kuckertz, A., & Kayser, I., (2012). Cannibalization or synergy? Consumers' channel selection in online-offline multichannel systems. *Journal of Retailing and Consumer Services*, *19*(2), 186–194.
40. Lai, C. P., Shacham, A., & Bergman, K., (2010). Demonstration of asynchronous operation of a multiwavelength optical packet-switched fabric. *IEEE Photonics Technology Letters*, *22*(16), 1223–1225.
41. Larsson, E. G., Edfors, O., Tufvesson, F., & Marzetta, T. L., (2014). Massive MIMO for next generation wireless systems. *IEEE Communications Magazine*, *52*(2), 186–195.
42. Letaief, K. B., & Zhang, W., (2009). Cooperative communications for cognitive radio networks. *Proceedings of the IEEE*, *97*(5), 878–893.
43. Liu, Y., Chen, H. H., & Wang, L., (2016). Physical layer security for next generation wireless networks: Theories, technologies, and challenges. *IEEE Communications Surveys & Tutorials*, *19*(1), 347–376.
44. Liu, Y., Qin, Z., Elkashlan, M., Ding, Z., Nallanathan, A., & Hanzo, L., (2017). Non-orthogonal multiple access for 5G and beyond. *Proceedings of the IEEE*, *105*(12), 2347–2381.

45. Llano, G., Reig, J., & Rubio, L., (2010). Analytical approach to model the fade depth and the fade margin in UWB channels. *IEEE Transactions on Vehicular Technology*, *59*(9), 4214–4221.
46. Loyka, S. L., (2001). Channel capacity of MIMO architecture using the exponential correlation matrix. *IEEE Communications Letters*, *5*(9), 369–371.
47. Loyka, S., & Gagnon, F., (2004). Performance analysis of the V-BLAST algorithm: An analytical approach. *IEEE Transactions on Wireless Communications*, *3*(4), 1326–1337.
48. Loyka, S., & Kouki, A., (2001). The impact of correlation on multi-antenna system performance: Correlation matrix approach. In *IEEE 54th Vehicular Technology Conference, 2*, 533–537.
49. Malik, W. Q., Allen, B., & Edwards, D. J., (2007). Fade depth scaling with channel bandwidth. *Electronics Letters*, *43*(24), 1371–1372.
50. Matsubara, A., Tomiki, A., Toda, T., & Kobayashi, T., (2011). Measurements and characterization of ultra-wideband propagation within spacecrafts—Proposal of wireless transmission for replacing wired interface buses. *Advances in Spacecraft Technologies*, *3, 2–12*.
51. Minden, G. J., Evans, J. B., Searl, L. S., DePardo, D., Rajbanshi, R., Guffey, J., & Agah, A., (2007). Cognitive radios for dynamic spectrum access-an agile radio for wireless innovation. *IEEE Communications Magazine*, *45*(5), 113–121.
52. Moustakas, A. L., Simon, S. H., & Sengupta, A. M., (2003). MIMO capacity through correlated channels in the presence of correlated interferers and noise: A (not so) large N analysis. *IEEE Transactions on Information Theory*, *49*(10), 2545–2561.
53. Mueck, M., Piipponen, A., Kalliojärvi, K., Dimitrakopoulos, G., Tsagkaris, K., Demestichas, P., & Hayar, A., (2010). ETSI reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards. *IEEE Communications Magazine*, *48*(9), 78–86.
54. Muhammad, K., Staszewski, R. B., & Leipold, D., (2005). Digital RF processing: Toward low-cost reconfigurable radios. *IEEE Communications Magazine*, *43*(8), 105–113.
55. Mukherjee, A., Fakoorian, S. A. A., Huang, J., & Swindlehurst, A. L., (2014). Principles of physical layer security in multiuser wireless networks: A survey. *IEEE Communications Surveys & Tutorials*, *16*(3),

1550–1573.

56. Nicholl, G., Gustlin, M., & Trainin, O., (2007). A physical coding sublayer for 100 GbE [Applications & Practice]. *IEEE Communications Magazine*, *45*(12), 4–10.
57. Novak, D., & Waterhouse, R., (2013). Advanced radio over fiber network technologies. *Optics Express*, *21*(19), 23001–23006.
58. Roberts, M. L., Temple, M. A., Mills, R. F., & Raines, R. A., (2006). Evolution of the air interface of cellular communications systems toward 4G realization. *IEEE Communications Surveys & Tutorials*, *8*(1), 2–23.
59. Sadek, A. K., Han, Z., & Liu, K. R., (2006). A distributed relay-assignment algorithm for cooperative communications in wireless networks. In: *2006 IEEE International Conference on Communications* (Vol. 4, pp. 1592–1597).
60. Sadek, A. K., Su, W., & Liu, K. R., (2006). Multinode cooperative communications in wireless networks. *IEEE Transactions on Signal Processing*, *55*(1), 341–355.
61. Saeed, N., Celik, A., Al-Naffouri, T. Y., & Alouini, M. S., (2019). Underwater optical wireless communications, networking, and localization: A survey. *Ad Hoc Networks*, *94*, 101935.
62. Scaglione, A., Goeckel, D. L., & Laneman, J. N., (2006). Cooperative communications in mobile ad hoc networks. *IEEE Signal Processing Magazine*, *23*(5), 18–29.
63. Schaefer, R. F., & Boche, H., (2014). Physical layer service integration in wireless networks: Signal processing challenges. *IEEE Signal Processing Magazine*, *31*(3), 147–156.
64. Shaukat, S. F., Hassan, M., Farooq, R., Saeed, H. U., & Saleem, Z., (2009). Sequential studies of beamforming algorithms for smart antenna systems. *World Applied Sciences Journal*, *6*(6), 754–758.
65. Sherman, M., Mody, A. N., Martinez, R., Rodriguez, C., & Reddy, R., (2008). IEEE standards supporting cognitive radio and networks, dynamic spectrum access, and coexistence. *IEEE Communications Magazine*, *46*(7), 72–79.
66. Shiu, D. S., Foschini, G. J., Gans, M. J., & Kahn, J. M., (2000). Fading correlation and its effect on the capacity of multielement antenna systems. *IEEE Transactions on Communications*, *48*(3), 502–513.

67. Shiu, Y. S., Chang, S. Y., Wu, H. C., Huang, S. C. H., & Chen, H. H., (2011). Physical layer security in wireless networks: A tutorial. *IEEE Wireless Communications*, *18*(2), 66–74.

68. Sipal, V., Gelabert, J., Allen, B., Stevens, C., & Edwards, D., (2011). Frequency-selective fading of ultrawideband wireless channels in confined environments. *IET Microwaves, Antennas & Propagation*, *5*(11), 1328–1335.

69. Stojmenovic, I., Nayak, A., Kuruvila, J., Ovalle-Martinez, F., & Villanueva-Pena, E., (2005). Physical layer impact on the design and performance of routing and broadcasting protocols in ad hoc and sensor networks. *Computer Communications*, *28*(10), 1138–1151.

70. Su, W., Sadek, A. K., & Liu, K. R., (2005). SER performance analysis and optimum power allocation for decode-and-forward cooperation protocol in wireless networks. In: *IEEE Wireless Communications and Networking Conference* (Vol. 2, pp. 984–989).

71. Su, W., Sadek, A. K., & Liu, K. R., (2008). Cooperative communication protocols in wireless networks: Performance analysis and optimum power allocation. *Wireless Personal Communications*, *44*(2), 181–217.

72. Tang, F., Deneire, L., Engels, M., & Moonen, M., (2001). A general optimal switching scheme for link adaptation. In: *IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings* (Vol. 3, pp. 1598–1602).

73. Tang, F., Deneire, L., Engels, M., & Moonen, M., (2001). Adaptive link adaptation. In: *GLOBECOM'01. IEEE Global Telecommunications Conference* (Vol. 2, pp. 1262–1266).

74. Tao, X., Xu, X., & Cui, Q., (2012). An overview of cooperative communications. *IEEE Communications Magazine*, *50*(6), 65–71.

75. Tarokh, V., Jafarkhani, H., & Calderbank, A. R., (1999). Space-time block codes from orthogonal designs. *IEEE Transactions on Information Theory*, *45*(5), 1456–1467.

76. Tarokh, V., Seshadri, N., & Calderbank, A. R., (1998). Space-time codes for high data rate wireless communication: Performance criterion and code construction. *IEEE Transactions on Information Theory*, *44*(2), 744–765.

77. Tartakovsky, A. G., Li, X. R., & Yaralov, G., (2003). Sequential detection of targets in multichannel systems. *IEEE Transactions on Information Theory*, *49*(2), 425–445.

78. Telatar, E., (1999). Capacity of multi-antenna Gaussian channels. *European Transactions on Telecommunications*, *10*(6), 550–570, 585–595.

79. Thompson, J. S., Grant, P. M., & Mulgrew, B., (1996). Smart antenna arrays for CDMA systems. *IEEE Personal Communications*, *3*(5), 16–25.

80. Tu, Y. S., & Pottie, G. J., (2002). Coherent cooperative transmission from multiple adjacent antennas to a distant stationary antenna through AWGN channels. In: *Vehicular Technology Conference. IEEE 55th Vehicular Technology Conference* (Vol. 1, pp. 130–134).

81. Van Veen, B. D., & Buckley, K. M., (1988). Beamforming: A versatile approach to spatial filtering. *IEEE ASSP Magazine*, *5*(2), 4–24.

82. Vishwanath, S., Jindal, N., & Goldsmith, A., (2003). Duality, achievable rates, and sum-rate capacity of Gaussian MIMO broadcast channels. *IEEE Transactions on Information Theory*, *49*(10), 2658–2668.

83. Wang, N., Wang, P., Alipour-Fanid, A., Jiao, L., & Zeng, K., (2019). Physical-layer security of 5G wireless networks for IoT: Challenges and opportunities. *IEEE Internet of Things Journal*, *6*(5), 8169–8181.

84. Waqas, S. A., Jawad, M., Khan, I., Mahmood, M. A., Shah, I. A., & Jan, S., (2013). Path(s) finding and selection technique for multi-hop mesh cooperative networks. *Bahria University Journal of Information & Communication Technology*, *6*(1), 50.

85. Winters, J. H., (2006). Smart antenna techniques and their application to wireless ad hoc networks. *IEEE Wireless Communications*, *13*(4), 77–83.

86. Wu, Y., Khisti, A., Xiao, C., Caire, G., Wong, K. K., & Gao, X., (2018). A survey of physical layer security techniques for 5G wireless networks and challenges ahead. *IEEE Journal on Selected Areas in Communications*, *36*(4), 679–695.

87. Zafar, B., Gherekhloo, S., & Haardt, M., (2012). Analysis of multihop relaying networks: Communication between range-limited and cooperative nodes. *IEEE Vehicular Technology Magazine*, *7*(3), 40–47.

88. Zhou, X., Ganti, R. K., & Andrews, J. G., (2010). Secure wireless network connectivity with multi-antenna transmission. *IEEE Transactions on Wireless Communications*, *10*(2), 425–430.

Chapter 5

Medium Access Control Layer

CONTENTS

5.1. INTRODUCTION

Network node mostly has the potential of the point-to-point communiqué, as when for the signal reception and transmission, it is fortified with techniques of a PHY. Though, for networking amongst several nodes, this is inadequate for some reasons.

Firstly, to understand bitstreams and change them into packets or vice versa, there is a need for an interface between higher and PHY protocols. Then, in order to organize the reception and transmission of packets between several nodes to enhance network performance, algorithms, and mechanisms of operation are needed. This kind of function is known as medium access control (MAC) (Ali et al., 2006). Third, although the most progressive algorithms of channel coding are adapted, still errors can occur in packets and bits. Due to fluctuations in interference, link quality, and several other factors, this is specifically accurate for wireless networks. So, on the PHY top, further error control is typically needed.

As we discussed the differences between mobile ad hoc networks (MANETs) and WMNs in the last chapters, existing error and MAC control schemes planned for MANETs, due to different design structures and network characteristics, are not essentially applicable to WMNs (Ali et al., 2006; Langendoen, 2008).

Organizing the process of sharing a similar medium between various users to attain specific performance goals is the main activity of a MAC protocol. QoS and throughput are included in typical metrics of performance, e.g., packet loss ratio, delay, and delay jitter, etc.

MAC can be divided into two main kinds, based on which network node takes care of the medium access coordination and these types are: *distributed MAC and centralized MAC*.

A centralized node coordinates and controls the whole process, and to approach the network, all other nodes must rely on this node, and all this process occurs in centralized MAC protocol. This group includes several wireless networks. For instance, infrastructure mode wireless LANs, satellite networks, cellular networks, etc. Since the network is distributed itself basically, so distributed MAC is preferable in multichip wireless networks (Ye et al., 2004). For these networks, if a centralized MAC is used so due to the need for maintaining the centralized control between several nodes, it does not have sufficient efficacy. Moreover, the MAC protocol scalability is also hindered by it. Due to this, distributed MAC is highly important for WMNs and also for MANETs. Though, it is clear that than designing a centralized MAC, a distributed MAC designing is a much more challenging activity (Raviraj et al., 2006).

As MACs' lower part is directly made upon the methods of a PHY, so usually there is no clarity between the PHY and MAC. For instance, some general various access schemes such as CDMA, TDMA, or OFDM have been observed in the PHY. These general various access schemes are not replaced by MAC protocol (Kuntz et al., 2009).

As an alternative, for the MAC protocol design, it is necessary to take them as an initial point. There are various main parts of MAC protocol:

- **Packet Processing and Queuing for Both Transmission and Reception:** This is a boundary between the upper layer and MAC protocols. When upper layer protocols send packets like the IP layer, packets are managed by putting some fields of error control such as CRC and MAC headers. When there is a need for security, then according to a specific encryption algorithm, the material of a packet desire to be ciphered (Lee et al., 2006). After completing all this process, packets are line up in the transmission, and wait for supplies (e.g., channels, time slots, codes, etc.), to initiate transmission. At receiving end, the whole process is executed oppositely so that they are received properly in the layer of MAC and directed to the upper layer.
- **Coordination of Medium Access:** This is the major part of a MAC protocol, which includes different tasks based on the kind of MAC protocols require to be designed:
  – For a MAC protocol based on reservation, the key task is to the allocation of resources like time slots, codes, channels, or subcarriers to users in a way to enhance the network throughput is the main activity but there is also the satisfaction of their QoS. At the end of this, there is a need to consider various other algorithms in the PHY, for instance, modulation, power control, and adaptive coding, etc. Moreover, transport layer's function and network function also need to be observed. Like, before, and after distribution of resources, due to huge variances of RTT, deliberate start performance of TCP may influence TDMA MAC (Kuntz et al., 2011). These demands suggest that the design of a cross-layer between other protocol layers and MAC is essential.

- Searching for the best solution for lessening collision is the main problem for a random-access MAC protocol such as CSMA/CA and from collision, fast recovery is still occurring. As there is no availability of reservation when a user's amount increases, collision becomes serious, and therefore the performance of throughput reduces greatly. Due to this, there is no guarantee of QoS. Though, there are two major benefits of random-access MAC protocols. Firstly, their simplicity. In the protocol, there is no need for separate reservation and signaling systems. Compatibility with Connectionless (datagram) networks like the Internet, is the second one (Elgazzar et al., 2013). In contrast, how to carry out the combination with a connectionless network is always the issue of a reservation-based MAC protocol. For instance, if a TDMA MAC is used, there should be a wait for distribution to be done, when a session of TCP begins. As it is assumed by TCP that the network is choked before even resource distribution is finished, so much delay is not TCP-friendly. One more instance is, there is no way for MAC to find out its QoS needs and bandwidth when video traffic is sent to the internet via TDMA MAC. Without such information, reservation cannot be completed properly, except dynamic slot of time distribution and estimation of adaptive resources are designed interactively. Though, these kinds of issues are not faced by random access MAC protocol, since as it attains, a packet begins its process of transmission (Haque et al., 2010).

- **Network Formation and Association:** For a MAC protocol, this is essentially the part of network management. It is responsible for the disassociation/association of a node from /to the network and the formation of the network when a node connects/disconnects the network. This is most significant for WMNs. Without association and formation, there is no identification between network nodes and initiate their MAC protocol consequently (Cho and Jeon, 2016).
- **Adaptive Rate Control:** Various current wireless networks' PHY has the potential of adaptive modulations and coding. For packet transmissions, there is a need of taking adaptive rate control for the MAC protocol to use this kind of potential properly. The

transmission time of packets also varies as the channel condition changes, due to the fluctuation of the transmission rate (Figure 5.1) (Al-Turjman et al., 2013).

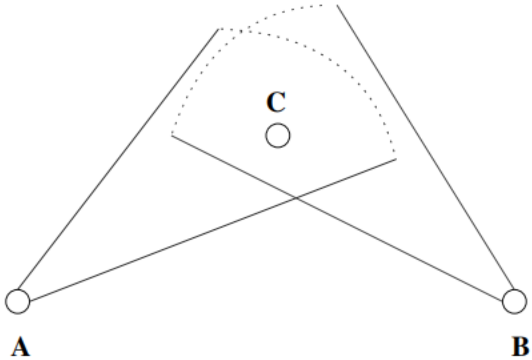


Figure 5.1. When using directional antenna, the hidden nodes are presented here.

Source: https://en.wikipedia.org/wiki/Hidden_node_problem.

5.2. SINGLE-CHANNEL SINGLE-RADIO MAC PROTOCOLS

5.2.1. CSMA/CA Improvements

CSMA/CA, which can be utilized in the ad hoc mode of IEEE 802.11 to make a meshed wireless LAN, is the most famous single-channel MAC protocol. To enhance its performance for WMNs, various systems have been suggested to fine-tune CSMA/CA. Following are the few categories of these systems (Figure 5.2) (Kwon et al., 2009):

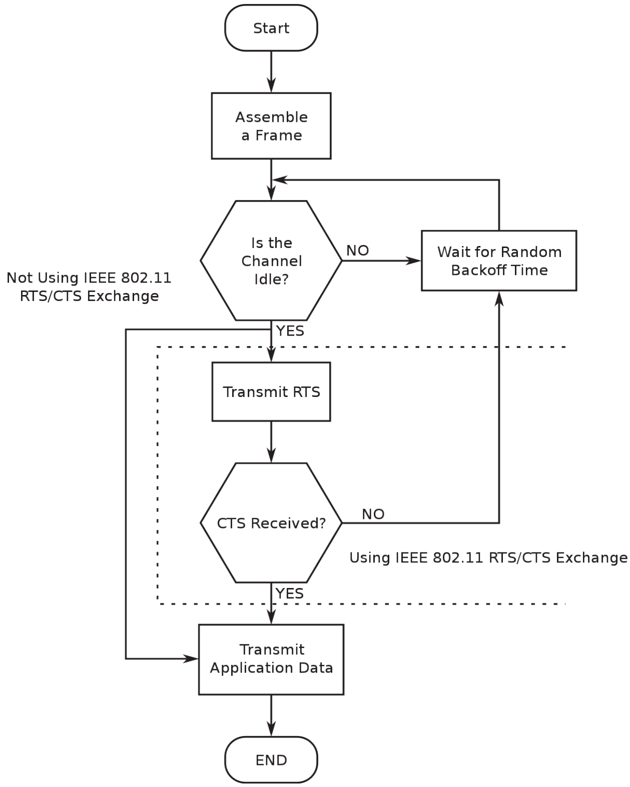


Figure 5.2. Basic CSMA/CA' algorithm.

Source: https://upload.wikimedia.org/wikipedia/commons/thumb/1/1d/Csma_ca.svg/1200px-Csma_ca.svg.png.

- Directional back-off is another arrangement to decrease the nodes (Shin, 2012). When a node finds a busy channel, it does not always postpone its transmission. Whether it determines if its destination will also find a busy channel. If not and the counter of backoff is zero, then from this node, transmission can be initiated, as the destination node will still be capable to accept a packet accurately.
- Adjust physical carrier sense. Both exposed node or hidden node problems can be caused by physical carrier sense: various nodes convert into exposed nodes when there is huge sensitivity; when there is low sensitivity, few nodes hide from one another. So, for utilizing a range of dynamic carrier senses, few offers have

been mentioned in Wu et al. (2008). Though, there is a research problem that how to make a scheduling outline in the network for all nodes to fine-tune the range actively. In the actual application of an IEEE 802.11 wireless LAN card, in CSMA/CA, the sensing range threshold used is arranged with the value that a node can sense the transmission of other nodes which are more than two hops away. The physical carrier sense must be adapted to be directional to decrease the number of exposed nodes. The use of a directional antenna on nodes is a broadly accepted technique (Liu et al., 2014). So, Node A can convey packets during Node B's transmission simultaneously and it is out of the coverage of Node B. There are three disadvantages of a directional antenna. The first one is, exposed nodes occur for nodes in the exposure of one another. Furthermore, the network is separated when nodes are not in the coverage of each other and so needs dynamic tuning of the antenna beam, which enhances the cost and complexity. Lastly, there will be the appearance of hidden nodes. For instance, in Figure 5.1, Node A and Node B do not have coverage of one another, and Node C is under cover of Node A and Node B. So, Node A and Node B can be the reason for a clash at Node C and make hidden nodes to each one.

- Dynamic tuning of the back-off procedure. There are different ways to back off the procedure. Firstly, as an alternative to binary exponential backoff, a different backoff can be used. As it is not well-matched with CSMA/CA stated in IEEE 802.11, it is not preferable. The allocation of different maximum and minimum contention windows in the network for different nodes is another technique. Though, the question is, to enhance throughput performance, how efficient this technique can be. In Liu et al. (2018), a technique that vigorously tunes the window of contention is discussed. In this technique, p-persistent back-off approximates the back-off. The optimal persistence factor p_{min} is measured based on this model and also in the network, the approximated active stations number. The contention window is figured as $2/p_{min} - 1$ with p_{min}. The throughput performance of CSMA/CA could be enhanced by this technique and it is presented by simulations. Though, it is depending on various conventions. In this technique, to send subsequent Poisson processes, each node is expected to have packets. Furthermore, the active stations can be predicted. Additionally, based on approximated collisions, the approximated number of active stations approximated idle periods, and so on, the optimal persistent factor can be measured. Specifically, in a WMN environment, all these conventions do not match a real network.

- Directional back-off is another arrangement to decrease the nodes (Ma et al., 2007). When a node finds a busy channel, it does not always postpone its transmission. Whether it determines if its destination will also find a busy channel. If not and the counter of backoff is zero, then from this node, transmission can be initiated, as the destination node will still be capable to accept a packet accurately.
- Improve virtual carrier sense. Virtual carrier sense can be the reason for extra exposed nodes and can decrease hidden nodes efficiently. There is a need for a virtual carrier sense of direction to decrease the number of exposed nodes. When both Omni-antennas and directional antennas occur in the same network, based on demand to send/clear to send (RTS/CTS) matches the situations, the virtual carrier sense operate and its operation is confirmed by directional virtual carrier sense which is discussed in Jung and Lim (2011). Though, there is the need to develop directional virtual carrier sense schemes alike to directional back off, when all nodes use antennas of omnidirectional. Such techniques depend on support among neighboring nodes and the accessibility of topology information.

The aforementioned methods can be used to enhance the efficiency of CSMA/CA. Though, the problems of scalability of CSMA/CA remains a challenging task and cannot be fixed by any of the methods used, as the protocol of MAC is a kind of protocol of CSMA/CA protocol in these methods.

5.2.2. IEEE 802.11e

The efficiency of CSMA/CA is hoped to be enhanced by the aim of IEEE 802.11e, to support a definite level of QoS. The hybrid coordination function (HCF) is the main function that has been declared in IEEE 802.11e. There are two sub-functions associated with the HCF controlled channel access (HCCA) and enhanced distributed channel access (EDCA) (Figure 5.3) (Mangold et al., 2002).

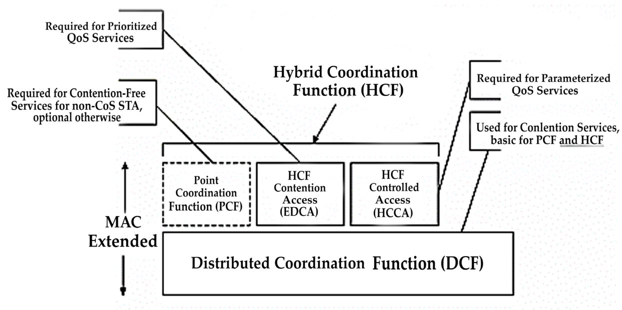


Figure 5.3. IEEE 802.11e MAC architecture.

Source: https://www.researchgate.net/figure/IEEE-80211e-MAC-architecture_fig1_224332895.

Provision of the selective entrance to various types of traffic makes the distributed coordination function (DCF) betters by EDCA. A similar method of traffic marking is used in EDCA as suggested in IEEE 802.1D. Hence, there are eight various priorities of traffic from the upmost layer (Xiao, 2005). Four access categories (ACs) are further drawn from the eight priorities in IEEE 802.11e, each of the four is given with diverse parameters such as CW_{min}, arbitrary inter-frame space, and CW_{max}. For the traffic of voice, for instance, the AIFS has the smallest value and the priority is highest and CW_{max} along with CW_{min}, is also the smallest. Moreover, lower-priority AC with a minimum contention window should not be greater than the access category (AC) a higher-priority having a maximum contention window. Both external contentions and internal contentions are present in the scheme on the basis of these priorities in various ACs. Various ACs for internal contentions of the same node are designed to contest with one another to decide the AC for the initiation of the communications. After this decision, ACs should compete with each other from the different nodes (Choi et al., 2003; Hui and Devetsikiotis, 2005). EDCA transmission opportunity is given to the node which wins the process contention. In the beacon, the length of EDCA transmission opportunity is determined. Length of the packet and TXOP determine the number of packets to be transferred by the node in this period. Fragmentation is required in case when the length of TXOP is smaller than that of a packet. On the other hand, multiple packets can be delivered to the TXOP (Ni, 2005).

It is worth noting that conferring to DCF a legacy node attempts to access the channel having IEEE 802.11e.

QoS access point sends a QoS polling information QoS CF_Poll and allocates a TXOP to a QoS station in a HCF Controlled Channel Access. Polled TXOP is the name given to this type of TXOP and it is present in both *contention-free period (CFP) and contention period* in every beacon period. QAP decides the length of the polled TXOP in the information of QoS CF_Poll. Polled TXOP can also offer QoS assurances to multimedia traffic, in addition to the scheduling systems and traffic specifications (Xiao, 2004). In the mode of infrastructure, HCCA, and EDCA can offer QoS sustenance to nodes. IEEE 802.11e is not valid in a WMN situation due to the following reasons:

- For QoS sustenance, EDCA is only a per-hop design. It cannot guarantee any sustenance for endwise QoS, even if it operates impeccably.
- A true QoS sustenance is not provided by the EDCA. To prioritize the access of the channel, EDCA depends on the contention widow and AIFS. This design is flawless for the same node ACs. Though, AC with lower priority having backoff counter of a node can extend to zero before the node having AC with higher priority, taking into account different nodes. The cause behind this behavior lies in the fact that the AIFS and contention window on dissimilar nodes are not coordinated (Mangold et al., 2003; Gao et al., 2005).
- Harder QoS can be offered by HCCA compared to EDCA, yet it relies on the accessibility of QAP. These types of the central controller might not be obtainable in WMNs. Furthermore, to upkeep end-to-end QoS, HCCA also depends on the end-to-end scheduling systems and TSPEC. The scope of IEEE 802.11e cannot incorporate these complex mechanisms. Hence, additional research is needed on the application of HCCA on WMNs to study their behavior. Taking TSPEC is another challenge from high layer protocols to HCCA, in IP networks specifically when resource-reservation protocol (RSVP) is not maintained (Kong et al., 2004).

5.2.3. WMN MAC Based on IEEE 802.11s

As discussed before, IEEE 802.11 assumed CSMA/CA can be used straight for application on WMNs. A number of issues can originate from this type of system. Initially, on the upper part of CSMA/CA, a routing protocol is required. Though, for MANETs, a number of routing protocols have been suggested, which can be weighty for WMNs. Moreover, various routing protocols can't operate with one another at the same time. Additionally, the topology of WMNs needs to be formed and maintained by the protocols, which is quite changed from a conventional wireless LAN (Figure 5.4) (Hiertz et al., 2007).

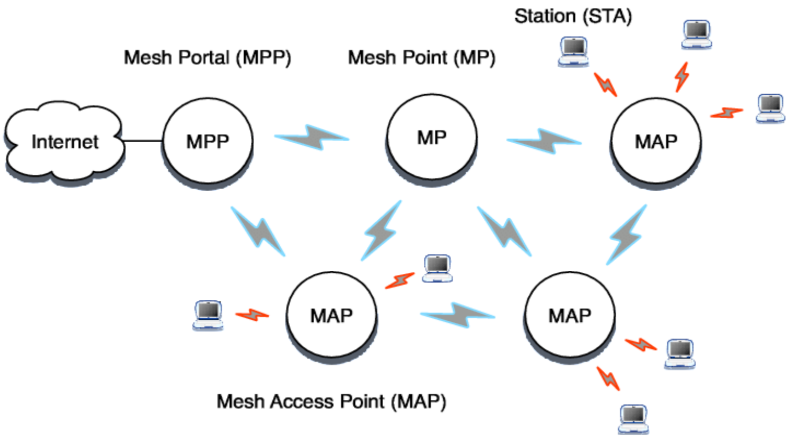


Figure 5.4. Terms in IEEE 802.11s: A mesh portal attaches to the wired Internet, a mesh point straight on mesh traffic, and a mesh access point furthermore permits stations to link with it.

Source: https://www.researchgate.net/figure/IEEE-80211s-terms-A-Mesh-Portal-MPP-connects-to-the-wired-Internet-a-Mesh-Point-MP_fig2_3200401.

Both MAC layer and routing operations are specified in IEEE 802.11s. In the initial draft of the standard of IEEE 802.11s there is mention of topology development, network architecture, end-to-end protocol stack reference model, possible routing protocols optimal multichannel operation, etc. Though, many operations do not lie under the scope of the IEEE 802.11s. For instance, IEEE 802.11s does not specify how to mesh point legacy clients of IEEE 802.11. Other examples include the absence of a thorough algorithm for the allocation of a channel in the mode of multichannel in the standard of IEEE 802.11s. Contrary to this, there are a number of functions that will be added in the final version of the draft and currently are being developed requiring further discussions (Chakraborty et al., 2013).

A number of possible problems can be found after revising the complete draft of IEEE 802.11s:

- The issue of scalability of CSMA/CA has not been resolved in MMNs, and a number of proposals are being submitted of IEEE802.11s to adjust the CSMA/CA protocol in the atmosphere of WMN. Though, adjustment of parameters is not enough to solve the problem of scalability. This kind of system can help to solve the issue of inter-working. The scalability can only be solved by the operation of multichannel. Though, the scope of IEEE 802.11s does not cater for the detailed design of the interaction between the multichannel operation and CSMA/CA (Hiertz et al., 2010).
- In the existing draft, the cross-layer is maintained poorly, while routing protocol is straight relocated to the layer of MAC and is stated in IEEE 802.11s. The operations of the routing layers and MAC function evidently to one another as in a conventional design of IEEE 802.11 WMNs. The performance and efficiency of the network do not seem to be enhanced by such as system (Wang and Lim, 2008).
- QoS has not been taken into account in IEEE 802.11s. Since the IEEE 802.11e is not valid to WMNs, there are absences of a solution in IEEE 802.11s to QoS sustenance of multimedia traffic.

5.2.4. TDMA Over CSMA/CA

A new system design is offered in (256), in place of just adjustment of the parameters of CSMA/CA to make its efficiency better. The new system assimilates CSMA/CA together with TDMA. Following are the main functions offered by the novel MAC protocol:

- Use of improved time synchronization function (TSF) to synchronize the node of 802.11 MAC;
- TDMA frame structure and scheduling system are planned to upkeep network access of legacy nodes of CSMA/CA;
- To organize packet transmissions unresponsive nodes in WMNs a disseminated scheduling system is established. QoS of this scheduling system is taken in time slot distribution;
- In 802.11 MAC, to deactivate the hardware level retransmission, software retransmission is suggested. Reception and packet

transmission can be restricted, on the basis of software retransmission, to a specific time, and therefore crossing slot-boundary is evaded.

A multichannel mode has been suggested in order to make the efficiency of TDMA better over CSMA/CA (Zikria et al., 2015). Following main functions are offered:

- A channel provision and a time slot algorithm are needed for the allocation of channels and time slots simultaneously by taking into account the demands of the traffic, network topology, and QoS.
- In order to overcome the overhead because of the switching of the channel, the switching of the channel required improvement. However, the processes in MAC can be of longer periods, the physical operation of switching of a channel can be as fast as less than 100 μs. Therefore, the process of switching the channel requires optimization in MAC.

The system design of CSMA/CA MAC protocols requires programming by software to install the above TDMA MAC protocols on the basis of CSMA/CA. Though, with the advancement of the chipset design, such type of the system design is considered a common practice for the design of MAC protocol. There are many advantages of TDMA over CSMA/CA:

- It is quite well-matched with CSMA/CA protocol (Kim and Lee, 2007; Gilani et al., 2013);
- Absence of the recognized issues of a CSMA/CA protocol. Therefore, fairness, QoS, and output of WMNs on the basis of such MAC protocol have far enhanced features in comparisons with CSMA/CA;
- It has a multichannel operation of which gives enhanced performance compared to other prevailing multichannel MAC (MMAC) protocols, as channel switching and switching are synchronized in a TDMA approach;
- There are potential advantages to the other protocols including mobility management transport, routing, etc., owing to its TDMA approach.

5.2.5. MAC for Ultra-Wideband (UWB) WMNs

A number of customer devices of electronics in the small home office can be connected by wireless personal area networks (WPANs) with high speed.

Examples include high-speed broadcast of HDTV signals, videos, images, requiring a large amount of data in between HDTV, PC, camcorder, video player, and so on. UWB is considered one of the most favorable technology in such a situation to support communications in high speed as it has a very low consumption of power and it gives a high transmission rate (Max et al., 2007; Khatun et al., 2009).

IEEE 802.15.3 standard has been used for the PHY and MAC technologies. In 2003, the initial version of IEEE 802.15.3 got its approval. In this method of standardization, the piconet concept is the basis of the MAC. Though, there are diverse specifications of MAC protocol approved by ECMA and proposed by the WiMedia Alliance for UWB WPAN of high speed (Shrestha et al., 2014). In the ECMA-368 standard, the MAC mostly comprises prioritized contention access (PCA) based on distributed TDMA and CSMA. In a comparison of the MAC between the IEEE 802.15.3 standards and standards of ECMA-368, it has been observed that the same structure has been followed by the superframe: CFP, contention access period (CAP), and a beacon period. The variation is only observed in the management and control of the CFP and CAP.

The mesh networking ability has neither been identified by ECMA-368 nor by IEEE 802.15.3. Though, this capability is needed for a number of reasons by the UWB-based WPANs because of their growing demand. Enhancing network coverage is one prime reason, not to affect the power transmission and rate of transmission. There are other reasons such as avoiding failure at a single point, making reliability better, and so on. Presently, IEEE 802.15.5 Researchers have been working on to identify the mesh networking capability. Though, the proposal has not been finalized in detail (De-Domenico et al., 2010; Shahin et al., 2018).

5.3. MULTI-CHANNEL SINGLE-RADIO MAC PROTOCOLS

The communication range in a single-channel MAC protocol is much lower than the interference range, the channel efficiency in terms of time-spatial-reuse is low, and hence, as the nodes number or as the hops number are increased it results in a decrease in network capacity. A number of channels can be utilized to overcome the limitations of capacity by interference in the unchanged network. As a matter of fact, in various channels, a number of radios can work today. IEEE 802.11b/g radios, for instance, can operate in three non-overlapping channels, and the quantity of non-overlapping channels is too large in IEEE 802.11a (Campbell et al., 2011).

There are two choices in to use various channels in the same network contingent upon the number of channels that operate in parallel on the identical node. Various nodes in the same network may utilize various channels at the same time, but only one channel can be used by the single node at a time if the node contains one radio having a single transceiver. Various nodes in the same network can use multiple channels if a node contains a number of radios and also same node can utilize multiple channels. It is worth noting that on the same node, a number of radios can be installed as one NIC or multiple NICs on which a number of radios exist by the radio-on-chip (RoC) or system-on-chip (SoC) method (Campbell et al., 2011).

Either for multiple or single radio nodes, to proficiently use the existing channels, a multi-channel MAC protocol is needed in the network.

Various pairs of receiver and sender are needed when nodes only contain a single radio in order to utilize dissimilar channels at the same time. Though, it is not possible to fix the channel linked to a pair of receiver and sender, as a load of traffic on the pair of receiver and sender is changing with time. Hence, channels for these pairs of receiver and sender are required to be reorganized on time. A proficient MAC protocol is required for this type of dynamical reorganization, and also on every radio, switching of channels is required (Zhang et al., 2007).

5.3.1. Multichannel MAC (MMAC Protocol)

For ad hoc networks, MMAC was suggested in (Maheshwari et al., 2006). Though, MMAC was essentially more suitable for WMNs as mobility was not an issue in the structure. MMAC accepts that the basis of the fundamental methods of a wireless node lies on IEEE 802.11 CSMA/CA protocols with supported RTS/CTS. Finding the solution for the issue of multichannel node is the goal of the MMAC for multichannel operation when the IEEE 802.11 MAC is used for application. Hence, it is important to examine the issue of a multichannel hidden nodes before further discussing the procedure and working of the MMAC.

5.3.2. Slotted Seeded Channel Hopping (SSCH) MAC

For gaining the advantage of the simple placement of this technology on present IEEE 802.11 wireless networks, SSCH functions accurately according to the standard IEEE 802.11 protocol. Following are the concepts regarding the SSCH (Bahl et al., 2004).

- The hopping of the channel is done in a slot-by-slot manner, in order to synchronize various hopping programs on various nodes. Hence, there is a need to coordinate nodes in the network;
- On various nodes, a number of schedules of channel hopping are utilized so that: no reasonable dividing wall occurs in the network and interference is as low as possible between these nodes;
- As no central controller is existing in WMNs, the schedules of channel hopping require determination in a distributed manner (Bian et al., 2011).
- **Distributed Slotted Channel Hopping:** There are possibilities of hopping slot by slot from one channel to other in SSCH. No interference will take place if the channels of the destination and source pair in the range of the interference are dissimilar, taking into account any time slot. This scenario is best suited for the multichannel function. To find the best-suited schedule of the channel hopping, there is a need for the scheduling scheme. SSCH depends on an arbitrary process with a distinctive seed produce autonomous schedules of the channel hopping without a centralized controller in WMNs (Figure 5.5) (Chao and Tsai, 2004).

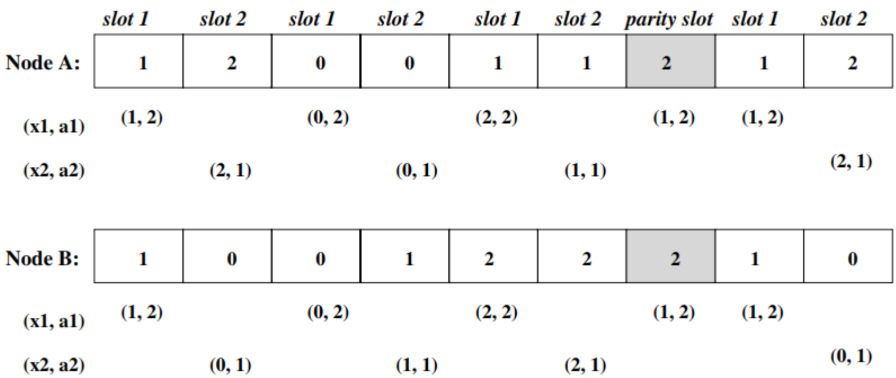


Figure 5.5. A channel updating in SSCH.

Source: https://onlinelibrary.wiley.com/doi/10.1002/9780470059616.ch3.

Following three necessities are to be fulfilled for the channel updating program to have an efficient performance of MAC (Sahoo and Sahoo, 2016; Chao et al., 2017):

- Adjacent nodes must have various other channels in a similar time slot to avoid the chances of the collision. Hence, nodes mustn't contain information for one another which would be ensured by the schedule of the channel hopping to decrease the overlapping frequency of the channel as much as possible.
- At the same time, there must be a common channel for two adjacent nodes. Else, there are chances of logical partition in the network.
- There should be some channels overlapping in some time slots for the nodes which contain information for one another.

There are three situations for two nodes to assess the efficiency of the channel apprising scheme in 3.2:

- **The Seeds of Such Two Nodes are Dissimilar:** After the updates in the channel, it can be verified that between these two nods there is only one channel in overlapping situations. So, necessities 1, 2, and 3 may be fulfilled. Nevertheless, there is no provision in the case when two-node need to send more information through a common channel (Chao et al., 2015).
- **Channels and Seeds Linked with Seeds are the Same:** Channels, in such cases between the two nodes, remain the same. Hence, the necessities 2 and 3 may be definite always. Nevertheless, necessity 1 would be disturbed in a case when the two nodes do not contain information for one (Tan et al., 2017).
- **Channels Linked with Seeds are Dissimilar, but the Seeds are the Same:** So, all the time, no two nodes will have the common channel. It has been proved by simple mathematics that the possibility of such a scenario is too low. Nevertheless, the two nodes would not be able to communicate with one another if such a situation arises, and a logical partition in the network will be its consequence. Hence to overcome this issue, after every $m \times n$ time slot, an extra time slot is incorporated, and in this time slot, the channel always remains a_1. Hence, there is an overlapping channel for each node with time slots of $m \times n + 1$. *Parity slot* is the name given to this extra slot (Li et al., 2017).

As discussed, is an overlapping channel for each node with a parity slot without having any logical partition in the network. Nevertheless, the variation in the load results in a loss of ability to capture the dynamics of the network by the channel updating program given in 3.2. Consequently, there are two possibilities, either the nodes are unable to attain enough time slots to propel their packets with the overlapping channels or the chances of the collision between the nodes become high. A mechanism is required to select the (seed, channel) pair carefully, to get the dynamics of the network for every node and every time slot. Regrettably, no such mechanism was suggested to perform this task; only a modest method was suggested (Chang et al., 2012). In this method, the packet is inspected by the node and then selection of the (seed, channel) pair takes place having the best chance for the node to send the packets to the required nodes.

This method is very simple but has some problems as addressed below:

- Packets receiving importance of the node is not taken into account;
- Congestion of the channel is not considered.

The first problem is solved by SSCH which keeps a counter for every m slot to determine the quantity of the packets expected during the time of one update iteration of the channel in this slot. The slot is termed as *receiving slot* provided there are more than 10 packets received at this slot. Just non-receiving slots are permitted to change during the selection of the (seed, channel) pairs.

For the latter problem, a comparison is performed by SSCH of the (seed, channel) pairs of the sender node to the pairs of the other nodes. There is a need to desynchronize nodes if the quantity of the other nodes is two times more than the sender node.

Hou et al. (2011) demonstrated the results that the efficiency of SSCH is far better than the IEEE 802.11 MAC. Though, there are numerous problems associated that restrict the efficiency in WMNs, as discussed below.

5.3.2.1. Issues in SSCH

There are a number of issues with SSCH, although it makes the efficiency of the IEEE 802.11 MAC better in WMNs:

- **The Supposition on Delay in Channel Switching is Not Accurate:** A delay of 80 μs in channel switching is presumed. Though, any of the IEEE 802.11 wireless cards are not supported to achieve this delay time. A number of various jobs take part in both PHYs and MAC to make the delay in channel switching larger. The anticipated scheme in SSCH is not able to perform in a way to attain improvement in performance as displayed in (24) taking into account the larger delays in channel switching (Wang and Huang, 2010).

- **No Mechanism for the Selection of (Seed, Channel) Pair:** For a node, a simple method has been suggested for the selection of (seed, channel) pair in SSCH. Though, various (seed, channel) pairs between various nodes are not synchronized by this method. Hence, there are high chances of conflict between the selected (seed, channel) pair on a node and with another node, and it will have the disadvantage of having no multichannel communications. The suggested mechanism does not have any synchronization between various nodes, though circumstances of congested channels and receiving slots are taken into account (Wang and Huang, 2010).
- **With a Variable Traffic Load, the Channel Updating Mechanism may Not be Efficient:** The (channel, seed) pair should be dynamically selected, to get the dynamics of a network because of the load of the traffic. Nevertheless, one reiteration of the channel hopping program requires time slots of $m \times n + 1$, as clarified in the channel updating mechanism. With a variable traffic load, the (channel, seed) pair should be selected much before the completion of the reiteration of the channel hopping program. Contrary to this, the efficiency of the channel hopping program completely relies on the complete and steady reiterations of channel updates in every slot in SSCH.

5.4. CHANNEL ASSIGNMENT IN THE MAC LAYER

For a multi-channel MAC protocol, the assignment of channels has always been a critical task. All currently working MAC protocols take this step into account. Though, there are researches in which it has been claimed that there are a number of MAC protocols that do not consider an algorithm that can feasibly assign channels to nodes based on the dynamics of the network and variations between the nodes because of the changing load of traffic (Gong et al., 2007; Wu et al., 2009). Hence, to make the efficiency of the MAC protocol better, there is a need to improve the channel assignment step. Huang et al. (2008) suggested a mechanism of channel assignment on the basis of reducing the effect of neighboring nodes on each other. Du et al. (2007) executed a mechanism of coordinated channel assignment to measure the channel assignment for a mesh network of distributed multichannel TDMA MAC of 802.11 and to measure the non-conflict time. Sun et al. (2012) performed a dynamic channel allocation mechanism in which many data channels and a common control channel are formed by the division of the accessible channels. Furthermore, many data interfaces and one common control interface are formed by the division of the accessible interfaces. The Control channel gets the control interface assignment permanently. Every node here maintains a list of free channels and current idle. Node A sends an FCL and RTS information to the single control channel when it needs to communicate with node B. An idle channel is selected by the receiver node after comparison of the FCL from the sender to its own FCL and then forms its CTS message by including all this information in it. Afterward, both Nodes B and A change their data interfaces to the designated channel and begin and initiate transmission of data (Mustafa et al., 2012).

For certain kinds of WMN including WMNs with a central root node (21) or WMN, some channel assignment algorithms have been suggested. Hou et al. (2011) Established an algorithm of channel assignment on the basis of the distance-1 edge coloring (D1EC) containing a gateway node as the origin of the whole topology, and usually, this gateway is used for the traffic flow. Allocation of channel for a network would be free of contention if distance-1 edge coloring occurs for a graph. Though the distance-1 edge coloring might not be present or distance-1 edge coloring issue can be NP-complete random topologies of a network. Hence, on the basis of the distance-1 edge coloring, an empirical mechanism has been suggested below. An empirical mechanism is utilized to search for the results if the distance-1 edge coloring is present; or else, the affected channels are reduced by the algorithm. Consequently, there will be some links having no contentions but some links having negligible interference in a distance-1 edge coloring channel assignment algorithm. Additionally, for the MAC protocol, such data of interference is useful for competition with a channel more proficiently. The distance-1 edge coloring channel assignment algorithm has a goal to make the best use of the collective network output of single-radio WMNs. This mechanism is static assignment based, and hence is it is not valid for the situations in which the load of the traffic is variable. The algorithm is not valid either for the general kinds of WMNs (Mustafa et al., 2012).

Specific code systems are used for the channel assignment including superimposed code for multi-radio WMNs (Vallati and Mingozzi, 2015). In such systems, a channel code is kept by every node which specifies a bundle of secondary and primary channels of this particular node. The assignment of the channel to this specific node is measured on the basis of the data from the neighboring nodes and local nodes. There is some issue related to the channel assignment based on the superimposed code. Initially, an equal number of the radios are assumed by it on each node, which does not stand true for the common WMN. This scheme is not applicable in extreme situations such as single-radio WMNs. Additionally, the load of the traffic on every node radio ought to be consistent. Else, the assignment of a channel on each radio instead of each link does not provide promising results. Moreover, the number of radios is not mandatorily lower than the non-interfering channels. In 802.11n, for instance, the quantity of non-interfering channels is not greater than the radios. Lastly, it is not sometimes possible to determine the interfering node, or is extremely difficult to find this node (Martinez and Wetzel, 2007). Hence, assignment of the channel on the basis of the codded information of interfering nodes is not suitable always.

5.5. DYNAMIC FREQUENCY SELECTION (DFS) REQUIREMENTS

There are some rules which must be obeyed when a multichannel process is performed on a radio. In IEEE 802.11a, for instance, however, there are almost twelve channels in overlap, but that does not guarantee the use of MAC protocol for any of these, as radar signals may get affected by the IEEE 802.11a devices, and in various countries, it is not permitted such as USA, Japan, and European Union (Selvakumar and Revathy, 2018). DFS necessities quantified by various standards ought to be fulfilled if it is necessary to use these channels without affecting the radar signals.

Various parameters of the system and various procedures are specified in several standards for DFS, however, a similar structure is followed by the necessities, as discussed below:

- The device in a network that starts the communications should obey DFS. Since in a mesh network every node is capable of doing so, hence the availability of DFS at each mesh node must be ensured (Zeng et al., 2019).
- The DFS starts its work by checking the presence of channels before the selection of channels. Channel availability check time is the period required by the DFS to check the channel. Normally,

DFS takes about 60 seconds for the checking of the availability of the channel.

- Channel is used by the node after the availability of the channel for communication. Though, a node must check for the radar signals (Selvakumar and Revathy, 2019).
- Normally, a node starts a transfer to other channels once the signals from the radar are sensed. Simply speaking, a node sends a message to all other neighbors which are using the very channel to shut their channel down. Channel move time is the period required from sensing the signals from radar to the shutdown of the channel. This process completes in about 10 seconds. Control of total transmission time is also mandatory during the time. Channel closing transmission time can be referred to as the total transmission time which accounts for about 250 milliseconds (Selvakumar and Revathy, 2018).
- The node attempts to find another accessible channel after a shutdown of the first channel. After the channel, accessibility check time has gone and a new channel has been found, switching of the node to the new channel takes place (Selvakumar and Revathy, 2018).

A particular system should be suggested for a MMAC protocol to obey DFS at a time when MAC protocol is approved in a product. In such a situation, considering DFS, re-evaluation of all the currently working MMACs must be performed (Chakraborty et al., 2013; Girgis et al., 2014).

REFERENCES

1. Ali, M., Saif, U., Dunkels, A., Voigt, T., Römer, K., Langendoen, K., & Uzmi, Z. A., (2006). Medium access control issues in sensor networks. *ACM SIGCOMM Computer Communication Review*, *36*(2), 33–36.
2. Al-Turjman, F. M., Hassanein, H., Oteafy, S., & Alsalih, W., (2013). Towards augmenting federated wireless sensor networks in forestry applications. *Personal and Ubiquitous Computing*, *17*(5), 1025–1034.
3. Bahl, P., Chandra, R., & Dunagan, J., (2004). SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks. In: *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking* (Vol. 3, No. 1, pp. 216–230).
4. Bian, K., Park, J. M., & Chen, R., (2011). Control channel establishment in cognitive radio networks using channel hopping. *IEEE Journal on Selected Areas in Communications*, *29*(4), 689–703.
5. Campbell, C. E. A., Loo, K. K., Gemikonakli, O., Khan, S., & Singh, D., (2011). Multi-channel distributed coordinated function over single radio in wireless sensor networks. *Sensors*, *11*(1), 964–991.
6. Chakraborty, D., Debbarma, M. K., & Roy, S., (2013). QoS Provisioning in WMNs: Challenges and a comparative study of efficient methodologies. *International Journal of Computer Applications*, *65*(3) 6–19.
7. Chakraborty, S., Swain, P., & Nandi, S., (2013). Proportional fairness in MAC layer channel access of IEEE 802.11 s EDCA based wireless mesh networks. *Ad Hoc Networks*, *11*(1), 570–584.
8. Chang, G. Y., Teng, W. H., Chen, H. Y., & Sheu, J. P., (2012). Novel channel-hopping schemes for cognitive radio networks. *IEEE Transactions on Mobile Computing*, *13*(2), 407–421.
9. Chao, C. M., & Tsai, H. C., (2014). A channel-hopping multichannel MAC protocol for mobile ad hoc networks. *IEEE Transactions on Vehicular Technology*, *63*(9), 4464–4475.
10. Chao, C. M., Fu, H. Y., & Zhang, L. R., (2015). A fast rendezvous-guarantee channel hopping protocol for cognitive radio networks. *IEEE Transactions on Vehicular Technology*, *64*(12), 5804–5816.
11. Chao, C. M., Tsai, H. C., & Huang, C. Y., (2017). Load-aware channel hopping protocol design for mobile ad hoc networks. *Wireless Networks*, *23*(1), 89–101.

12. Cho, T. H., & Jeon, G. M., (2016). A method for detecting man-in-the-middle attacks using time synchronization one time password in interlock protocol-based internet of things. *Journal of Applied and Physical Sciences*, *2*(2), 37–41.
13. Choi, S., Del Prado, J., & Mangold, S., (2003). IEEE 802.11 e contention-based channel access (EDCF) performance evaluation. In: *IEEE International Conference on Communications, 2003. ICC'03* (Vol. 2, pp. 1151–1156).
14. De Domenico, A., Strinati, E. C., & Di Benedetto, M. G., (2010). A survey on MAC strategies for cognitive radio networks. *IEEE Communications Surveys & Tutorials*, *14*(1), 21–44.
15. Du, P., Jia, W., Huang, L., & Lu, W., (2007). Centralized scheduling and channel assignment in multi-channel single-transceiver WiMAX mesh network. In: *2007 IEEE Wireless Communications and Networking Conference* (Vol. 6, No. 1, pp. 1734–1739).
16. Elgazzar, K., Ejaz, A., & Hassanein, H. S., (2013). AppaaS: offering mobile applications as a cloud service. *Journal of Internet Services and Applications*, *4*(1), 1–12.
17. Gao, D., Cai, J., & Ngan, K. N., (2005). Admission control in IEEE 802.11 e wireless LANs. *IEEE Network*, *19*(4), 6–13.
18. Gilani, M. H. S., Sarrafi, I., & Abbaspour, M., (2013). An adaptive CSMA/TDMA hybrid MAC for energy and throughput improvement of wireless sensor networks. *Ad Hoc Networks*, *11*(4), 1297–1304.
19. Girgis, M. R., Mahmoud, T. M., Abdullatif, B. A., & Rabie, A. M., (2014). Solving the wireless mesh network design problem using genetic algorithm and tabu search optimization methods. *Int. J. Comput. Netw. Wirel. Commun*, *4*(2), 1–8.
20. Gong, M. X., Midkiff, S. F., & Mao, S., (2007). A cross-layer approach to channel assignment in wireless ad hoc networks. *Mobile Networks and Applications*, *12*(1), 43–56.
21. Haque, A., Murshed, M., & Ali, M., (2010). Efficient contention resolution in MAC protocol for periodic data collection in WSNs. In: *Proceedings of the 6th International Wireless Communications and Mobile Computing Conference* (Vol. 12, No. 6, pp. 437–441).
22. Hiertz, G. R., Denteneer, D., Max, S., Taori, R., Cardona, J., Berlemann, L., & Walke, B., (2010). IEEE 802.11 s: the WLAN mesh standard. *IEEE Wireless Communications*, *17*(1), 104–111.

23. Hiertz, G. R., Max, S., Zang, Y., Junge, T., & Denteneer, D., (2007). IEEE 802.11 s MAC fundamentals. In: *2007 IEEE International Conference on Mobile Ad Hoc and Sensor Systems* (Vol. 2, No. 3, pp. 1–8).
24. Hou, F., Cai, L. X., Shen, X., & Huang, J., (2011). Asynchronous multichannel MAC design with difference-set-based hopping sequences. *IEEE Transactions on Vehicular Technology*, *60*(4), 1728–1739.
25. Huang, R., Zhai, H., Zhang, C., & Fang, Y., (2008). SAM-MAC: An efficient channel assignment scheme for multi-channel ad hoc networks. *Computer Networks*, *52*(8), 1634–1646.
26. Hui, J., & Devetsikiotis, M., (2005). A unified model for the performance analysis of IEEE 802.11 e EDCA. *IEEE Transactions on Communications*, *53*(9), 1498–1510.
27. Jung, J., & Lim, J., (2011). Group contention-based OFDMA MAC protocol for multiple access interference-free in WLAN systems. *IEEE Transactions on Wireless Communications*, *11*(2), 648–658.
28. Kao, H. H., Wu, P. J., & Lee, C. N., (2011). Analysis and enhancement of multi-channel MAC protocol for ad hoc networks. *International Journal of Communication Systems*, *24*(3), 310–324.
29. Khatun, S., Saeed, R. A., Nordin, N. K., & Ali, B. M., (2009). Ultra-wideband solutions for last mile access network. In: *Encyclopedia of Multimedia Technology and Networking* (Vol. 2, No. 1, pp. 443–1452).
30. Kim, H., Yun, S., & Lee, H., (2007). Boosting VoIP capacity of wireless mesh networks through lazy frame aggregation. *IEICE Transactions on Communications*, *90*(5), 1283–1285.
31. Kim, Y. G., Wang, Y., Park, B., & Choi, H. H., (2016). A heuristic resource scheduling scheme in time-constrained networks. *Computers & Electrical Engineering*, *54*, 1–15.
32. Kong, Z. N., Tsang, D. H., Bensaou, B., & Gao, D., (2004). Performance analysis of IEEE 802.11 e contention-based channel access. *IEEE Journal on Selected Areas in Communications*, *22*(10), 2095–2106.
33. Kuntz, R., Gallais, A., & Noel, T., (2009). Medium access control facing the reality of WSN deployments. *ACM SIGCOMM Computer Communication Review*, *39*(3), 22–27.

34. Kuntz, R., Gallais, A., & Noël, T., (2011). From versatility to auto-adaptation of the medium access control in wireless sensor networks. *Journal of Parallel and Distributed Computing*, *71*(9), 1236–1248.
35. Kwon, H., Seo, H., Kim, S., & Lee, B. G., (2009). Generalized CSMA/CA for OFDMA systems: Protocol design, throughput analysis, and implementation issues. *IEEE Transactions on Wireless Communications*, *8*(8), 4176–4187.
36. Langendoen, K., (2008). Medium access control in wireless sensor networks. *Medium Access Control in Wireless Networks*, *2*, 535–560.
37. Lee, S. H., Hwang, S. W., Lee, H. J., & Lee, H. G., (2010). Low power MAC protocol design of an efficient preamble exploiting virtual synchronization scheme for wireless sensor networks. *The Journal of Korean Institute of Communications and Information Sciences*, *35*(5B), 762–770.
38. Li, A., Han, G., Rodrigues, J. J., & Chan, S., (2017). Channel hopping protocols for dynamic spectrum management in 5G technology. *IEEE Wireless Communications*, *24*(5), 102–109.
39. Liu, Q., Lu, Y., Hu, G., Lv, S., Wang, X., & Zhou, X., (2018). Cooperative control feedback: On backoff misbehavior of CSMA/CA MAC in channel-hopping cognitive radio networks. *Journal of Communications and Networks*, *20*(6), 523–535.
40. Liu, Q., Wang, X., Han, B., Wang, X., & Zhou, X., (2014). Access delay of cognitive radio networks based on asynchronous channel-hopping rendezvous and CSMA/CA MAC. *IEEE Transactions on Vehicular Technology*, *64*(3), 1105–1119.
41. Ma, L., Shen, C. C., & Ryu, B., (2007). Single-radio adaptive channel algorithm for spectrum agile wireless ad hoc networks. In: *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks* (Vol. 60, No. 5, pp. 547–558).
42. Maheshwari, R., Gupta, H., & Das, S. R., (2006). Multichannel MAC protocols for wireless networks. In: *2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks* (Vol. 2, pp. 393–401).
43. Mangold, S., Choi, S., Hiertz, G. R., Klein, O., & Walke, B., (2003). Analysis of IEEE 802.11 e for QoS support in wireless LANs. *IEEE Wireless Communications*, *10*(6), 40–50.

44. Mangold, S., Choi, S., May, P., Klein, O., Hiertz, G., & Stibor, L., (2002). IEEE 802.11e wireless LAN for quality of service. In: *Proc. European Wireless* (Vol. 2, pp. 32–39).
45. Martinez, J., & Wetzel, T., (2007). Practical advice for meeting the DFS testing requirements of the FCC. *Conformity*, *12*(9), 30–32.
46. Max, S., Weiss, E., & Hierz, G. R., (2007). Analysis of WiMedia-based UWB mesh networks. In: *32nd IEEE Conference on Local Computer* (Vol. 3, No. 1, pp. 919–926).
47. Mustafa, S., Madani, S. A., Bilal, K., Hayat, K., & Khan, S. U., (2012). Stable-path multi-channel routing with extended level channel assignment. *International Journal of Communication Systems*, *25*(7), 887–902.
48. Ni, Q., (2005). Performance analysis and enhancements for IEEE 802.11e wireless networks. *IEEE Network*, *19*(4), 21–27.
49. Peng, W., Chen, D., Sun, W., & Zhang, G., (2016). Distributed adaptive channel allocation in multi-radio wireless sensor networks. *J. Commun.*, *11*(11), 984–991.
50. Raviraj, P., Sharif, H., Hempel, M., & Ci, S., (2006). An energy efficient mac approach for mobile wireless sensor networks. In: *IEEE International Conference on Computer Systems and Applications* (Vol. 16, No. 7, pp. 565–570).
51. Sahoo, P. K., & Sahoo, D., (2016). Sequence-based channel hopping algorithms for dynamic spectrum sharing in cognitive radio networks. *IEEE Journal on Selected Areas in Communications*, *34*(11), 2814–2828.
52. Selvakumar, K., & Revathy, G., (2018). Channel assignment using Tabu search in wireless mesh networks. *Wireless Personal Communications*, *100*(4), 1633–1644.
53. Selvakumar, K., & Revathy, G., (2018). Sustain route by tabu and amplifying QOS with distributed scheduling in WMN. *Journal of Innovation in Electronics and Communication Engineering*, *8*(1), 7–12.
54. Selvakumar, K., & Revathy, G., (2019). Escalating quality of services with channel assignment and traffic scheduling in wireless mesh networks. *Cluster Computing*, *22*(5), 11949–11955.
55. Selvakumar, K., & Revathy, M. G., (2018). Increasing quality of services in wireless mesh networks. *International Journal of Advanced*

Research in Computer Engineering & Technology (IJARCET), *7*(3), 5–10.

56. Shahin, N., Ali, R., & Kim, Y. T., (2018). Hybrid slotted-CSMA/CA-TDMA for efficient massive registration of IoT devices. *IEEE Access*, *6*, 18366–18382.
57. Shi, W., Cui, K., & Chai, Y., (2016). Routing and channel assignment for multicast in multi-channel multi-radio wireless mesh networks. *J. Commun.*, *11*(11), 992–997.
58. Shin, B., (2012). A Multi-channel CSMA/CA scheme with packet aggregation on ad hoc networks with single radio devices. In: *International Conference on Future Information & Communication Engineering* (Vol. 5, No. 1, pp. 188–191).
59. Shrestha, B., Hossain, E., & Choi, K. W., (2014). Distributed and centralized hybrid CSMA/CA-TDMA schemes for single-hop wireless networks. *IEEE Transactions on Wireless Communications*, *13*(7), 4050–4065.
60. Sun, W., Fu, T., Xia, F., Qin, Z., & Cong, R., (2012). A dynamic channel assignment strategy based on cross-layer design for wireless mesh networks. *International Journal of Communication Systems*, *25*(9), 1122–1138.
61. Tan, X. J., Zhou, C., & Chen, J., (2017). Symmetric channel hopping for blind rendezvous in cognitive radio networks based on union of disjoint difference sets. *IEEE Transactions on Vehicular Technology*, *66*(11), 10233–10248.
62. Valarmathi, K., & Malmurugan, N., (2011). Distributed multichannel assignment with congestion control in wireless mesh networks. *International Journal of Communication Systems*, *24*(12), 1584–1594.
63. Vallati, C., & Mingozzi, E., (2015). Efficient design of wireless mesh networks with robust dynamic frequency selection capability. *Computer Networks*, *83*, 15–29.
64. Wang, J., & Huang, Y., (2010). A cross-layer design of channel assignment and routing in cognitive radio networks. In: *2010 3rd International Conference on Computer Science and Information Technology* (Vol. 7, pp. 542–547).
65. Wang, J., & Shi, W., (2016). Partially overlapped channels-and flow-based end-to-end channel assignment for multi-radio multi-channel wireless mesh networks. *China Communications*, *13*(4), 1–13.

66. Wang, X., & Lim, A. O., (2008). IEEE 802.11 s wireless mesh networks: Framework and challenges. *Ad Hoc Networks*, *6*(6), 970–984.
67. Wu, H., Yang, F., Tan, K., Chen, J., Zhang, Q., & Zhang, Z., (2006). Distributed channel assignment and routing in multiradio multichannel multihop wireless networks. *IEEE Journal on Selected Areas in Communications*, *24*(11), 1972–1983.
68. Wu, T. T., Kwong, K. H., Michie, C., & Andonovic, I., (2008). Self-organize multi-channel random selection medium access control protocol for wireless sensor networks. In: *2008 5th IEEE Consumer Communications and Networking Conference* (Vol. 9, No. 3, pp. 569–570).
69. Wu, Y., Keally, M., Zhou, G., & Mao, W., (2009). Traffic-aware channel assignment in wireless sensor networks. In: *International Conference on Wireless Algorithms, Systems, and Applications* (Vol. 6, No. 1, pp. 479–488).
70. Xiao, Y., (2004). IEEE 802.11 e: QoS provisioning at the MAC layer. *IEEE Wireless Communications*, *11*(3), 72–79.
71. Xiao, Y., (2005). Performance analysis of priority schemes for IEEE 802.11 and IEEE 802.11 e wireless LANs. *IEEE Transactions on Wireless Communications*, *4*(4), 1506–1515.
72. Ye, J., Wang, J. X., & Huang, J. W., (2011). A cross-layer TCP for providing fairness in wireless mesh networks. *International Journal of Communication Systems*, *24*(12), 1611–1626.
73. Ye, W., Heidemann, J., & Estrin, D., (2004). Medium access control with coordinated adaptive sleeping for wireless sensor networks. *IEEE/ACM Transactions on Networking*, *12*(3), 493–506.
74. Zeng, F., Zhao, N., & Li, W., (2019). Joint interference optimization and user satisfaction improvement for multicast routing and channel assignment in wireless mesh networks. *Cluster Computing*, *22*(6), 15059–15072.
75. Zhang, J., Zhou, G., Huang, C., Son, S. H., & Stankovic, J. A., (2007). TMMAC: An energy efficient multi-channel mac protocol for ad hoc networks. In: *2007 IEEE International Conference on Communications* (Vol. 4, No. 1, pp. 3554–3561).
76. Zhao, X., Zhang, S., Li, L., Qu, Z., Zhang, Y., Ding, Y., & Liu, J., (2018). A multi-radio multi-channel assignment algorithm based on topology control and link interference weight for a power distribution

wireless mesh network. *Wireless Personal Communications*, *99*(1), 555–566.

77. Zikria, Y. B., Nosheen, S., & Kim, S. W., (2015). Quality of service analysis for multimedia traffic using DSR, AODV, and TORA over Wi-Media ultra-wide band. In: *2015 12th International Bhurban Conference on Applied Sciences and Technology* (Vol. 12, No. 1, pp. 539–546).

Chapter 6

Fundamentals of Transport Layer

CONTENTS

6.1. INTRODUCTION

The layer of transport, like the layer of a network, offers different sorts of services connectionless and connection-oriented. Therefore, in this layer, the objective of providing these two sorts of services is distinct. In the link layer, network operations are governed by routing algorithms or other schemes of error control. Consumers, however, have no influence over these entities as well as networks will never be perfect (Parmar and Gosai, 2015; Habib et al., 2016). As a result, if a consumer wishes to send information through a network, they must depend upon the transport-layer protocol to meet the intends of a specific application. Specifically, the transport-layer protocol for the layer of application must support multiple transport layer QoS variables. Packet error ratio, throughput, and delay are common examples.

Transport protocols in WMNs will handle both non-real-time and real-time traffic. The traffic of real-time is largely unaffected by packet losses, although it is sensitive to delays. The traffic of non-real-time, on the other hand, is lenient of delays but needs consistency. As a result, real-time, and non-real-time traffic in WMNs requires distinct transport protocols (Figure 6.1) (Hanamsagar et al., 2015).

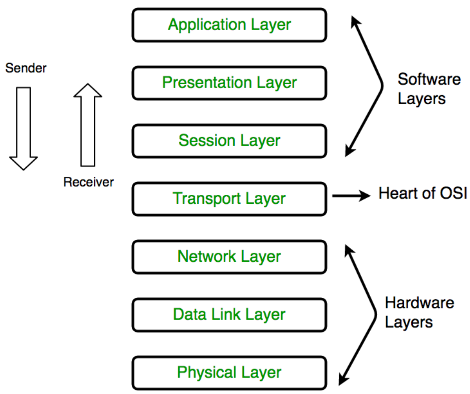


Figure 6.1. Mesh network's various layers.

Source: https://www.geeksforgeeks.org/layers-of-osi-model/.

In the last 3-decades, many transport protocols for wireless and wired networks have indeed been created. Just limited transport protocols have indeed been devised particularly for WMNs, to our knowledge. Because hoc and multihop networks and WMNs have several resemblances, current transport protocols of ad hoc networks are often discussed. We think that examining these protocols can bring useful guidance and insights for developing WMNs transport protocols. We conclude this chapter by highlighting the open research topics for WMNs depending on the analyzes of different transport-layer protocols (Bisht et al., 2016).

6.2. TRANSPORT LAYER PROTOCOL CHALLENGES IN WIRELESS ENVIRONMENTS

Whenever a transport protocol is used in wireless networks, it raises plenty of challenges.

6.2.1. Low Bandwidth

A wireless network typically has substantially less bandwidth accessible than a wired network. This necessitates a higher level of performance than a transport protocol can provide.

6.2.2. Large Bandwidth-Delay Product (BDP)

Certain wireless networks, like 802.11n, have recently seen large increases in link capacity. When used in multihop wireless networks, such as WMNs, the substantial end-to-end delay leads to a high bandwidth-delay product (BDP). For connectionless transport protocols, big BDP necessitates a high buffer at both the sender and receiver, as well as a wide congestion window with connection-oriented protocols of transport (Akan and Akyildiz, 2004).

Theoretical studies suggest that the TCP performance is optimal for a number of the congestion window fixed at n/4, with n representing the hops number, in idealized multihop conditions or with identical size packets (Caini et al., 2007). One option is to use protocols of split-connection (26), which minimizes the BDP within every split connection.

6.2.3. Frequent Blackouts

Network blackouts, like route failures or link failures, are common in wireless environments. In addition to congestion, poor connectivity can induce packet loss. The fact that conventional TCPs do not distinguish between noncongestion and congestion losses is among the well-known causes of TCP performance decline (Hsieh and Sivakumar, 2005). As a consequence, if there are noncongestion losses, the network performance declines quickly. Furthermore, when wireless channels are restored to normal functioning, the conventional TCP cannot immediately recover. The protocol in Bicen et al. (2012) improves TCP by using a feedback mechanism to distinguish among wireless channel and congestion losses. WMNs can benefit from this concept. TCP performance suffers as well when a link fails. Because all nodes in an ad hoc and mobile network are mobile, link failure is likely to happen frequently. So, the WMN infrastructure eliminates the problem of failure single-point, link loss is also not as crucial in WMNs as it does in ad hoc and mobile networks. Link failure is still possible due to mesh client mobility and wireless channels. Link and congestion failures should be distinguished to improve TCP efficiency. Differentiation can be accomplished with schemes like the explicit link failure notification (ELFN) mechanism (Ott and Kutscher, 2005).

6.2.4. Fluctuating RTT

An end-to-end packet delay fluctuates greatly over time, that can affect RTT calculation. RTT, on the other hand, is crucial to mostly all transport protocols, including TCP. The delay mechanism for TCP congestion management, for example, is dependent on RTT.

6.2.5. Network Asymmetry

Asymmetry of a network is characterized as a condition in which a network's forward and backward directions are significantly dissimilar in terms of latency, bandwidth, and loss rate (Ramaboli et al., 2012). ACK and Data packets of a transport protocol that is connection-oriented may travel distinct courses in a wireless network, particularly multihop networks such as WMNs, and hence experience differing bandwidth, packet loss rates (PLRs), and delay. Even if ACK and data packets travel a similar path, asymmetry network issues still exist since the condition of the channel and bandwidth on the route change with time and also are different in opposite directions. Network asymmetry can have a significant influence on the efficiency of a transport protocol that is connection-oriented like TCP. For instance, the ACK loss in the opposite route of the connection due to low link quality doesn't imply traffic in the forward direction with a similar connection. As a result, TCP performs poorly in wireless ad hoc and multihop networks (Kiess and Mauve, 2007; Mahmoud et al., 2014). Schemes like ACK congestion regulation, ACK filtering, and others have been developed to overcome the network asymmetry issue (Clark et al., 1987).

6.2.6. Heterogeneity

Whenever a transport protocol handles end-to-end interactions between wireless and wired networks, it encounters differences in the two networks' features. As a result, in both networks, the very similar mechanism and a set of variables cannot attain optimal efficiency. To fulfill the requirements of heterogeneous networks, one way is to divide a single connection over two or even many connections, and each has homogenous network features. One example is indirect TCP, in which a single end-to-end connection is divided into a wireless and wired connection, with two transport protocols employed (Paul et al., 1997). A further method for hiding duplicate acknowledgments (ACKs) or timeouts from the layer of transport is to use a snooping module throughout the network layer (Mudambi et al., 2006). But, like in the scenario for cellular networks, this strategy was only meant for a wireless network of one-hop linking to wired networks.

The abovementioned issues influence all kinds of transport-layer-protocols because those who interfere with various control mechanisms in the layer of transport, like stream control transmission protocol (SCTP), congestion control in TCP and flow control in SCTP and TCP, rate control in DCCP and datagram congestion control protocol (DCCP). Because of its simplification, the user datagram protocol (UDP) cannot be affected by such problems. In a wireless network, however, UDP performance might be substantially decreased.

The abovementioned concerns can be highly severe in WMNs:

- Numerous hops of wireless networks lead to a higher possibility of RTT fluctuation, link failure, packet loss, and path asymmetry;
- WMNs are often comprised of diverse wireless networks. As a result, transport protocols designed for wireless LANs or cellular networks are rarely applicable to WMNs. For instance, because it does not address the condition of a multihop wireless network, the snooping module suggested for cellular networks cannot be immediately used for WMNs (Zhai et al., 2007).

6.3. TRANSPORT LAYER PROTOCOLS FOR MULTIHOP AD HOC NETWORKS

Because a WMN's core network is essentially a multihop ad hoc network, the design methodology and standards provided for multihop ad hoc networks can be applied to WMNs. Adjustments may be required, however, due to the unique characteristics of WMNs (Figure 6.2).

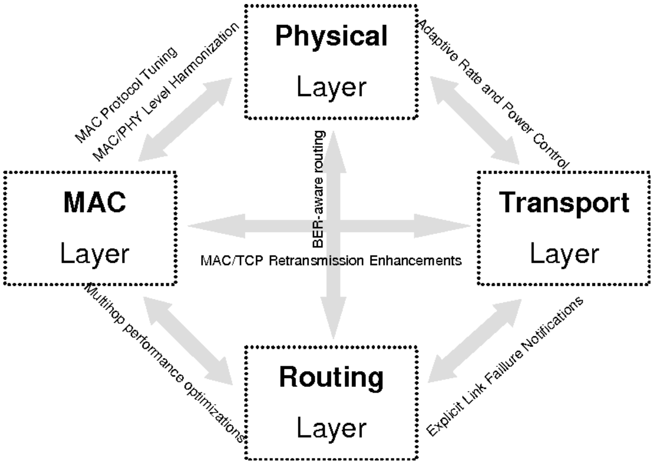


Figure 6.2. Transport layer, physical, routing, and MAC cross-layer optimizations.

Source: https://www.semanticscholar.org/paper/Cross-layer-optimizations-in-multi-hop-ad-hoc-Felice/4f2bb60ec603c30132e01042b3f082e128e9d9a4/figure/2.

6.3.1. Reliable Data Transport Protocols

For networks like multihop ad hoc, a wide variety of viable transport protocols have already been developed to date. There are two sorts of TCP variants: wholly new transport protocols and TCP variants. Relying on the wired networks classical TCP, a TCP version is created, that is strengthened by taking into account the unique properties of multihop ad hoc networks (Wang et al., 2009; Zafar and Town, 2011).

6.3.1.1. TCP Variants

In multihop ad hoc networks, the efficiency of classical TCPs falls substantially. Throughout this section, we look at a variety of upgraded TCP protocols by discussing the underlying issues with classical TCP and their solutions.

TCP variations can be grouped into numerous forms based on the various TCP elements that are influenced by the surroundings of a multihop ad hoc network: (1) acknowledgment optimization; (2) congestion differentiation and packet loss; (3) adaptive transmission rate control (4) window optimization (Wang et al., 2009).

6.3.1.2. Completely New Transport Protocols

As previously stated, TCP has several fundamental flaws. As a result, several researchers have begun to work on whole novel ad hoc network transport protocols.

The ad hoc transport protocol (ATP) for ad hoc networks is suggested in (Polese et al., 2019). In ATP, transmissions are rate-based, and speedy-start is employed to estimate beginning rates. Because the congestion identification is based on delay, there is no uncertainty among noncongestion and congestion losses. Furthermore, ATP has zero retransmission timeout and decouples congestion dependability and control. ATP outperforms TCP variations in terms of fairness, delay, and throughput by employing an altogether new set of techniques for accurate data delivery.

Despite its benefits, WMNs do not prefer an entirely new transport protocol due to compliance concerns. The wireless network is assumed to be self-contained by ATP. Although it may be valid for mobile ad hoc networks (MANETs). it is not true for wireless mesh networks (WMNs), as WMNs will be interconnected with the wireless networks and Internet. TCPs in other networks must be compatible with WMN transport protocols (Zafar and Town, 2011).

6.3.2. Real-Time Delivery Protocols

UDP, rather than TCP, is commonly used as a transportation protocol to assist the end-to-end transfer of real-time congestion. The simplest mechanism of UDP, on the other hand, cannot assure real-time transfer and may end TCP links on the same system. To operate over UDP, additional agreements like RTCP-real-time transport protocol- and RTP-real-time protocol-are required. For traffic control, RCP (rate-control protocol) is required in addition to RTCP or RTP (Wheeb, 2015).

Several RCP standards for wired connections have been suggested to date. They can be divided into two categories: additive increase multiplicative decrease (AIMD) based and equation-based. Due to the presence of link failures and packet errors, these standards are not pertinent to wireless networks. As a result, RCP must distinguish between damage incurred by overcrowding and damages done by wireless links. Different LDA_s-loss-differentiation-algorithms-with traffic control are investigated Wheeb (2015), with only one wireless connection on the route between receiver and sender being regarded. The hybrid-LDA is illustrated to be the most efficient one (Kumar and Rai, 2012). Moreover, because various wireless networks are present on the route between the sender and the receiver, this outcome may not be relevant to WMNs.

For end-to-end transfer of real-time congestion about both wireless and wired links, an analytical-rate-control strategy is suggested in. Conversely, more study is needed to see if this strategy is appropriate to WMNs.

For cellular networks, there are currently only a few rate-control strategies available. A n end-to-end multi-metric joint detection model is presented for TCP-friendly ADTFRC-an adaptive detection rate control-strategy, and rate-control strategies for cellular ad hoc networks was suggested. Moreover, the identification approach's precision is still inadequate to truly assist real-time delivery of multi-media congestion. Furthermore, all non-congestion packet loss caused by various issues is prepared in the same manner (Al-Akaidi, 2017). The rate-control scheme's efficiency may suffer as a result.

6.4. PROTOCOLS OF TRANSPORT LAYER FOR WMNS

For the causes listed below, there are currently only a few transport-layer protocols for WMNs. To begin with, when WMNs are implemented, other standards like MAC and routing are usually prioritized, and the transport-layer protocol is usually UDP or TCP. In practice, this procedure makes sense as a new transport agreement and improvement to a standard-transport-layer protocol necessitates the installation of a software patch to the operating system on a consumer's device and new software, including a handset or PC, that is not always desirable (Akyildiz and Wang, 2008). If MAC and routing, protocols can give sufficient quality and reliability to allow standard-transport protocols to be used. The consumers will have a more reliable solution, and system administrators and service providers will have a less complex process. Standard-transport-protocols, regrettably, cannot always fulfill the demands of several applications due to the complex issues raised in multi-hop wireless connections like WMNs. Second, some people may believe that the transport protocol suggested for ad hoc and mobile networks or other multi-hop webs can also be used for WMNs. These agreements, even so, may not be a better match for WMNs due to differences in characteristics between other multi-hop wireless connections and WMNs. Numerous TCP improvements for ad hoc networks, for instance, target path collapse due to mobility (Matsuo et al., 2018). After all, these incidents are uncommon in WMNs, particularly when the routing agreement is tailored to the unique characteristics of WMNs. Furthermore, the more established ad-hoc networks transport agreements only perceive a separated multi-hop wireless connection. WMNs' networks are usually attached to the Internet backbone through some portals, and a substantial quantity of traffic originates from or flows to the Internet backbone rather than circulating inside of WMNs. This type of network architectural design necessitates the consideration of two characteristics in a WMN's transport protocol. The first one is that we might not be able to ensure that the transit entity can be altered or modified as endpoints could be located within the network infrastructure instead of in WMNs (Akyildiz and Wang, 2005). Another is that traffic in WMNs is not distributed evenly, but it is more focused at endpoints nearer to the entry point. The connections between the transport layers and MAC in such a traffic design are substantially different from those in a general multi-hop wireless connection, as researched in a particular situation of WMNs, namely wireless back-haul connections in Sakamoto et al. (2018). As a consequence, arrangements like LRED and TCP-AP may not be capable of performing well in WMNs (Girgis et al., 2014; Sakamoto et al., 2019).

6.4.1. Hop-by-Hop Controlled Transport Protocols

Bit-error in data packets is the most common reason for packet loss in WMNs. This is in contrast to what happens in a mobile ad-hoc network, in which packet loss is primarily caused by link failures and routes. As a result, considering link layer performance improvement as a functional block of a transport agreement is a smart plan.

In the case of end-to-end transmissions at the transport-layer, if a packet is lost at a middle node owing to a bit error, the end-to-end transmissions not only wastes all the fruitful transmissions before this endpoint, but it also requires the packet to cross the same path anew, resulting in additional resource waste and postponement. Furthermore, even though postponed ACK schemes are used, end-to-end processes can create a large number of ACKs. These ACKs take up a significant amount of bandwidth (Carofiglio et al., 2012).

As a consequence, developing transport protocol based on hop-by-hop control is extremely coveted. Two different types of the transport protocol are described in the following sections.

For packets-lost owing to bit-error, a stateful-transport protocol is designed that uses hop-by-hop re-transmissions rather than end-to-end transmissions (Chakravarthi and Gomathy, 2011). This protocol is known as a "stateful" transport protocol because it necessitates routers within the system to sustain states for transport-layer operations. The heavy traffic control strategy in standard-TCP is not acceptable because most lost packets are retransmitted at the link-layer rather than end to end. As a result, heavy traffic control is carried out at the sender of a linkage using a rate-control method.

6.4.2. WMNs Datagram Congestion Control Protocol (DCCP)

DCCP performs as traffic control and is TCP friendly, so, it is preferable to utilize DCCP rather than UDP to assist multi-media applications in WMNs. As a result, evaluating DCCP's effectiveness over WMNs is intriguing. It presents some simulation results that illustrate DCCP's effectiveness in providing multi-media congestion than WMNs (Chakravarthi and Gomathy, 2011). If there is no contending non-DCCP transfers, DCCP can provide smooth output for multi-media applications. Conversely, if UCP or TCP flows are present, the smoothness swiftly decreases and may not be sufficient to meet the needs of multi-media congestion. As a result, the question of how to enhance DCCP's working over WMNs remains unsolved (Yuvaraj and Saravanan, 2021).

DCCP may have a significant influence than TCP or UDP when hop by hop rate control and re-transmission is being used for a credible transport protocol. It is also crucial to figure out how to make DCCP co-exist with this sort of modern efficient transport agreement.

6.5. OPEN RESEARCH PROBLEMS

As previously stated, many study questions remain unanswered for both real-times and reliable transport standards.

TCP-variant offers the benefits of easy compatibility and simplicity with standard-TCP agreements for credible transport standards. Since many TCP-variant designed for mobile ad-hoc networks can be used in WMNs, they are usually too complex. WMNs, for instance, may not be subject to rout damages or frequent links. As a result, more effective TCP improvement strategies for WMNs are anticipated. WMNs, in specific, require a congestion control algorithm, better loss-differentiation-scheme, re-transmission mechanism, and congestion detection scheme (Shuminoski and Janevski, 2016). Furthermore, because all problems with TCP efficiency deterioration are truly linked to protocols in the lowest layers therefore cross-layer improvement is a difficult but efficient method for reducing the influence of network asymmetry on TCP performance. The routing protocol, for example, specifies the route for both ACK packets and TCP data. To minimize asymmetry between ACK packets and data, a routing protocol must choose the best path both for ACK packets and data while reducing overhead. Researchers also realize that network asymmetry and packet loss ratio are directly influenced by link-layer effectiveness. As a result, the MAC layer might require to handle ACK packets and TCP data differently in an attempt to limit the risk of network asymmetry. According to Pulkkis et al. (2011), a MAC protocol such as CA/CSMA can starve congestion-controlled streams, similar to TCP, and so MAC protocol enhancements, such as counter-starvation policies based on contention-window, are required to improve the performance of the transport layer.

With a non-TCP-based dependable transport protocol, a cross-layer blueprint has been chosen. Rate control and re-transmission are mostly handled on the link-layer in LRTP. Nevertheless, enhancing the efficiency of these initiatives remains a challenge (Mahonen et al., 2001). Furthermore, how to build a stronger link or transport cross-layer standard with greater compatibility and performance with TCP is a fascinating topic. Because non-TCP trustworthy transport protocols do not match TCP semantics, yet WMNs are typically linked to consumers and nodes utilizing regular TCP, having a solution that supports standard-TCP reliability is crucial.

No current ad-hoc network system can be modified and adapted for the utilization of WMNs for real-time transmission. If UDP is used as a transport layer protocol, new RCPs must be created that take into account the characteristics of WMNs. If DCCP is used, its throughput must be improved to suit the requirements of multi-media applications in WMNs while also being amicable to TCP traffic (Kliazovich and Granelli, 2006; Hashimoto et al., 2011).

REFERENCES

1. Akan, O. B., & Akyildiz, I. F., (2004). ATL: An adaptive transport layer suite for next-generation wireless internet. *IEEE Journal on Selected Areas in Communications*, *22*(5), 802–817.
2. Akyildiz, I. F., & Wang, X., (2005). A survey on wireless mesh networks. *IEEE Communications Magazine*, *43*(9), 523–530.
3. Akyildiz, I. F., & Wang, X., (2008). Cross-layer design in wireless mesh networks. *IEEE Transactions on Vehicular Technology*, *57*(2), 1061–1076.
4. Alahmadi, H., & Bouabdallah, F., (2019). Multichannel preamble sampling MAC protocol for wireless sensor networks. *International Journal of Distributed Sensor Networks*, *15*(5), 157–191.
5. Al-Akaidi, M., (2017). A review on transport layer protocol performance for delivering video on an ad hoc network. *IOP Conference Series: Materials Science and Engineering*, *237*(1), 012018.
6. Bicen, A. O., Gungor, V. C., & Akan, O. B., (2012). Delay-sensitive and multimedia communication in cognitive radio sensor networks. *Ad Hoc Networks*, *10*(5), 816–830.
7. Bisht, N., Ahmad, A., & Bisht, S., (2016). Application of feature selection methods and ensembles on network security dataset. *International Journal of Computer Applications*, *135*(11), 1–5.
8. Caini, C., Firrincieli, R., Marchese, M., Cola, T. D., Luglio, M., Roseti, C., & Potorti, F., (2007). Transport layer protocols and architectures for satellite networks. *International Journal of Satellite Communications and Networking*, *25*(1), 1–26.
9. Carofiglio, G., Gallo, M., & Muscariello, L., (2012). Joint hop-by-hop and receiver-driven interest control protocol for content-centric networks. *ACM SIGCOMM Computer Communication Review*, *42*(4), 491–496.
10. Chakravarthi, R., & Gomathy, C., (2011). Hop-by-hop rate control technique for congestion due to concurrent transmission in wireless sensor network. *World Comput. Sci. Inf. Technol. J.*, *1*(8), 351–356.
11. Chiwariro, R., (2019). Wireless multimedia sensor networks-based quality of service sentient routing protocols: A survey. *Editorial Preface from the Desk of Managing Editor*, *10*(9), 5–10.

12. Chiwariro, R., (2020). Quality of service aware routing protocols in wireless multimedia sensor networks: survey. *International Journal of Information Technology*, 12 (2), 1–12.
13. Clark, D. D., Lambert, M. L., & Zhang, L., (1987). NETBLT: A high throughput transport protocol. *ACM SIGCOMM Computer Communication Review*, *17*(5), 353–359.
14. Girgis, M. R., Mahmoud, T. M., Abdullatif, B. A., & Rabie, A. M., (2014). Solving the wireless mesh network design problem using genetic algorithm and simulated annealing optimization methods. *International Journal of Computer Applications*, *96*(11), 5–10.
15. Habib, S., Qadir, J., Ali, A., Habib, D., Li, M., & Sathiaseelan, A., (2016). The past, present, and future of transport-layer multipath. *Journal of Network and Computer Applications*, *75*, 236–258.
16. Hanamsagar, A., Borate, B., Jane, N., Wasvand, A., & Darade, S., (2015). Detection of firewall policy anomalies in real-time distributed network security appliances. *International Journal of Computer Applications*, *116*(23), 4–10.
17. Hashimoto, M., Hasegawa, G., & Murata, M., (2011). A transport-layer solution for alleviating TCP unfairness in a wireless LAN environment. *IEICE Transactions on Communications*, *94*(3), 765–776.
18. Hsieh, H. Y., & Sivakumar, R., (2005). A transport layer approach for achieving aggregate bandwidths on multi-homed mobile hosts. *Wireless Networks*, *11*(1), 99–114.
19. Kiess, W., & Mauve, M., (2007). A survey on real-world implementations of mobile ad-hoc networks. *Ad Hoc Networks*, *5*(3), 324–339.
20. Kliazovich, D., & Granelli, F., (2006). Cross-layer congestion control in ad hoc wireless networks. *Ad Hoc Networks*, *4*(6), 687–708.
21. Kumar, S., & Rai, S., (2012). Survey on transport layer protocols: TCP & UDP. *International Journal of Computer Applications*, *46*(7), 20–25.
22. Li, S., Kim, J. G., Han, D. H., & Lee, K. S., (2019). A survey of energy-efficient communication protocols with QoS guarantees in wireless multimedia sensor networks. *Sensors*, *19*(1), 199.
23. Mahmoud, M. S. B., Pirovano, A., & Larrieu, N., (2014). Aeronautical communication transition from analog to digital data: A network security survey. *Computer Science Review*, *11*, 1–29.

24. Mahonen, P., Saarinen, T., Shelby, Z., & Muñoz, L., (2001). Wireless Internet over LMDS: Architecture and experimental implementation. *IEEE Communications Magazine*, *39*(5), 126–132.
25. Matsuo, K., Sakamoto, S., Oda, T., Barolli, A., Ikeda, M., & Barolli, L., (2018). Performance analysis of WMNs by WMN-GA simulation system for two WMN architectures and different TCP congestion-avoidance algorithms and client distributions. *International Journal of Communication Networks and Distributed Systems*, *20*(3), 335–351.
26. Mudambi, A. P., Zheng, X., & Veeraraghavan, M., (2006). A transport protocol for dedicated end-to-end circuits. In: *2006 IEEE International Conference on Communications* (Vol. 1, pp. 18–23).
27. Ott, J., & Kutscher, D., (2005). A disconnection-tolerant transport for drive-thru internet environments. In: *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies* (Vol. 3, pp. 1849–1862).
28. Parmar, H., & Gosai, A., (2015). Analysis and study of network security at transport layer. *International Journal of Computer Applications*, *121*(13), 35–40.
29. Paul, S., Sabnani, K. K., Lin, J. H., & Bhattacharyya, S., (1997). Reliable multicast transport protocol (RMTP). *IEEE Journal on Selected Areas in Communications*, *15*(3), 407–421.
30. Polese, M., Chiariotti, F., Bonetto, E., Rigotto, F., Zanella, A., & Zorzi, M., (2019). A survey on recent advances in transport layer protocols. *IEEE Communications Surveys & Tutorials*, *21*(4), 3584–3608.
31. Pulkkis, G., Grahn, K., & Karlsson, J., (2011). IT education topics for future networking. In: *In Site 2011: Informing Science+ IT Education Conference* (Vol. 11, pp. 443–470).
32. Ramaboli, A. L., Falowo, O. E., & Chan, A. H., (2012). Bandwidth aggregation in heterogeneous wireless networks: A survey of current approaches and issues. *Journal of Network and Computer Applications*, *35*(6), 1674–1690.
33. Sakamoto, S., Ozera, K., Barolli, A., Ikeda, M., Barolli, L., & Takizawa, M., (2019). Implementation of an intelligent hybrid simulation systems for WMNs based on particle swarm optimization and simulated annealing: Performance evaluation for different replacement methods. *Soft Computing*, *23*(9), 3029–3035.

34. Sakamoto, S., Ozera, K., Ikeda, M., & Barolli, L., (2018). Implementation of intelligent hybrid systems for node placement problem in WMNs considering particle swarm optimization, hill climbing and simulated annealing. *Mobile Networks and Applications*, *23*(1), 27–33.
35. Shuminoski, T., & Janevski, T., (2016). 5G mobile terminals with advanced QoS-based user-centric aggregation (AQUA) for heterogeneous wireless and mobile networks. *Wireless Networks*, *22*(5), 1553–1570.
36. Wang, R., Taleb, T., Jamalipour, A., & Sun, B., (2009). Protocols for reliable data transport in space Internet. *IEEE Communications Surveys & Tutorials*, *11*(2), 21–32.
37. Wheeb, A. H., (2015). Performance comparison of transport layer protocols. *International Journal*, *5*(12), 4–10.
38. Yuvaraj, N., & Saravanan, G., (2021). Markov transition and smart cache congestion control for IoT enabled wireless mesh networks. *Peer-to-Peer Networking and Applications*, *14*(1), 58–68.
39. Zafar, S., & Town, B. B. F., (2011). A survey of transport layer protocols for wireless sensor networks. *International Journal of Computer Applications*, *33*(1), 44–50.
40. Zhai, H., Chen, X., & Fang, Y., (2007). Improving transport layer performance in multihop ad hoc networks by exploiting MAC layer information. *IEEE Transactions on Wireless Communications*, *6*(5), 1692–1701.

Chapter 7

Telecommunications Applications of Mesh

CONTENTS

7.1. INTRODUCTION

Whether it is for capacity's self-production or spectral effectiveness, practical mobile meshes are not initially selected for this purpose and it is a widely recognized fact. The other advantages that accompany it are the reason that meshes are selected (Dan et al., 2005). Their chief quality is coverage advantages which were covered in Chapter two. The six most probable functions which were considered in the book are discussed here (Hongqi et al., 2005). They are:

- Office and home internal networking;
- Wi-Fi hotspot extension or cellular multi-hopping;
- Wireless sensor networks (WSNs);
- VANETS (vehicle ad hoc networks);
- Micro base station backhaul; and
- Communal networking.

This chapter goes into depth about the initial 5 applications. The overcoming of the obstacles presented to mesh adoption and the period needed for it will also be considered (Xiaoyu et al., 2004; Deepalakshmi and Radhakrishnan, 2014).

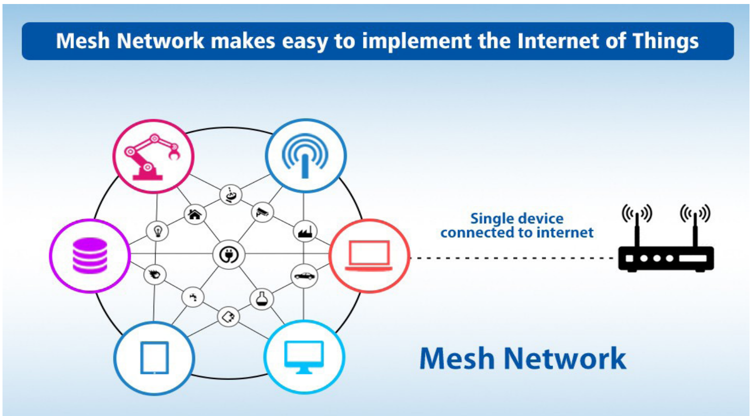


Figure 7.1. Internet of things (IoT) mesh system topology.

Source: https://iot.electronicsforu.com/expert-opinion/mesh-network-applications/.

The applications forming a mesh on the part of the user while those forming it on the part of the system will be grouped separately for the consequent discussion. It can also be seen as the meshing together of the nodes of the users itself vs. those where a mesh is formed only by the backhaul. However, in VANETs, the net backhaul and the user can both get the mesh (Figure 7.1) (Alam et al., 2016).

7.2. MESH FUNCTIONS FOR USER SIDE

Included in it are:

- Communal networking;
- Office and home internal networking;
- Wi-Fi hotspot extension or cellular multi-hopping.

Chapter 2 presented them along with pictures. Cell coverage can have a sufficient rise due to multi-hopping which is the main principle forming the base of the 3 applications (Zhang et al., 2017).

7.2.1. The Theory of Cell Boundary

Multi-hopping can lead to the functioning cell radius. For cell expansion, an upper bound is in existence and this will be shown by explaining and testing the theory as it is very significant to the meshing of the user side. It is believed that the upper bound's reason may not have been looked into. For instance, a TDMA system is used to present the outcome of complete traffic simulation design and the conclusion is that the extension of cell radius of arrangement x3 is possible. For the consequent reasons, it is believed that these approximations are on the greater side (Alotaibi and Mukherjee, 2012).

A huge system may face great traffic which puts forth a restriction that is not taken into account by the modeling paper. In the base station's straight span is the nodes' limited throughput capacity that is a restriction to range expansion. For the entire cell coverage, the traffic is carried by it.

An upper bound can be derived for cell expansion through the consideration of this feature. Through the nodes inside the range, the relaying of traffic to nodes is done outside the access point's trifling extent. A region that describes the annulus at the boundary of the range of the access point is where the traffic must go through. As shown in Figure 7.2, the annulus' breadth should be node to node (Mahajan et al., 2013).

The nodes' throughput is used up due to being a relay is thought to make an upper bound. This expression shows the occurrence of the great limitation of range expansion by taking the areas' ratio from a contemplation of the traffic intensity effect:

$$E\frac{X^2R^2 - R^2}{R^2 - (R - r)^2} \le (1 - E)$$

Where the average mobile to mobile contact extent is presented by r, the accessible traffic for each user (Erlang) is presented by E, the cell border expansion aspect is given by X, and the average access point to mobile contact span is given by R (Ganti and Haenggi, 2012).

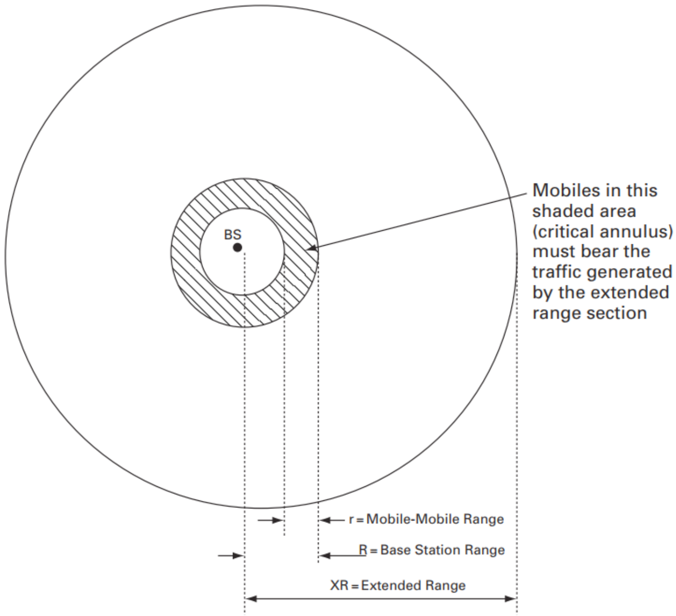


Figure 7.2. The footprint of cell border expansion.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/appropriate-telecommunications-applications-for-mesh/66E59498DAB9B82C5B45B6C069AF668F.

Following is the explanation of the above-mentioned expression's basis. The traffic volume in the annulus must be equivalent to or more than the external ring's traffic volume is how the condition of extensive traffic being relayed as used by the unemployed throughput is rephrased. Under such circumstances, the capacity which is not utilized must be 1E while the capacity that is utilized is E (Xu et al., 2011; Zhou and Zhuang, 2017). Thus, the suitable areas are found out by the use of geometry and then the equation can be made; the annulus' area is the denominator and the external ring's area is the numerator.

Furthermore, the node ranges and the access point's ratios are defined as:

Our expression becomes the following when Z= R/r.

$$E(X^2 - 1)\frac{Z^2}{2Z - 1} \leq (1 - E).$$

The user-controlled Erlang traffic loading, the resultant cell expansion element X, and the access point to node scope Z ratio which can be chosen are the significant factors. The traffic loading's square root is directly proportional to the range expansion which is implied by the fact that further things are repaired through design (Zhai et al., 2012).

Assumptions like constant user density, flawless load poising, and application have been made to derive the above-mentioned expressions. The use of mobile phones should be considered through the diagram. A 0.040 Erlang's hectic hour loading may be assumed. Ranging from 3.0 to 4.0 for a propagation law, and links of the node to node vs. margin base station's 13.0 to 20.0 dB extra link boundary, the span for Z is assumed to be 3.0 to 6.0 (Altieri et al., 2013).

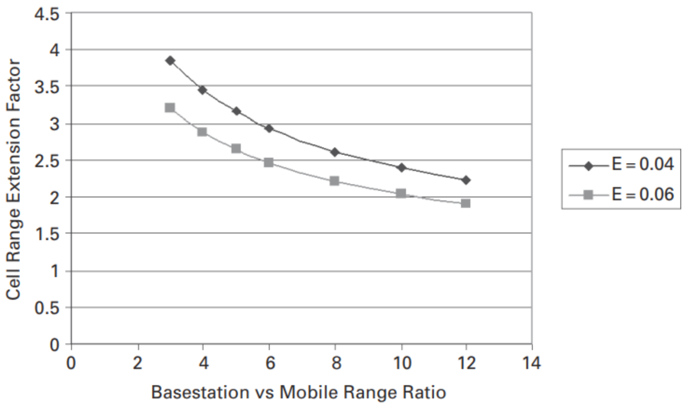


Figure 7.3. Upper limit (multi-hopping) showing the expansion of cell span.

Source: https://www.amazon.com/Essentials-Wireless-Mesh-Networking-Cambridge/dp/052187680X.

Through the rise of the access point to node span's ratio, the element of cell expansion can be increased which is an effort of weakening returns, however, this is an interpretation. Asymptotic limit is what the cell expansion element of 2.0 seems to look like. Keeping this in view, it would be a waste to design access point spans that are ten times more than node spans (Figure 7.3) (Behnad et al., 2013).

The three user-side mesh uses will be looked at now after describing the usual cell expansion code.

7.2.2. WLAN Hotspot Extension or Cellular Multi-Hop

Inside a WLAN system or cellular in the future, this is the possibility of multi-hopping amidst laptops, mobiles, PDAs (personal digital assistants), or various terminals. "Cellular with multi-hopping" is what this design is named as in the cellular field. In IEEE 802.16j, an application is in discussion in the field of data communication. To use the operation of relay is the notion to either (Lin and Wong, 2008):

- For the rise of obtainable coverage in a cell; or
- The expansion of the span of greater bandwidth facilities.

With few base locations and fewer infrastructure prices, such advantages are provided by them. Facilities being established at a greater rate than now, especially the less utilized spectrum is another advantage provided the details given in Part 4.7. Due to greater clutter loss and fewer link funds, getting greater rates from the current design of hotspot coverage or contiguous cellular is impossible. However, the innovative and cheap spectrum can be accessed by multi-hopping through relay nodes (Khan and Akbar, 2006).

A flaw in the instance of 3G is the meager obtainability of great data frequency facilities over a cell's coverage region, though it has the ability of greater frequency of transmission. A cheap solution to this would be preferred by the operators as they would not be willing to spend money on the needed extra infrastructure.

Multi-hop cellular is quite alike to the extension of the WLAN hotspot. But, the hopes of facilities are few due to which multi-hop cellular is difficult to deploy than Wi-Fi hotspot extension. For the facility guidelines' great worth of delay variation and delay, this is a supposed lesser need. Only elastic orders are put on the system like web browsing or email because of the current traffic kinds for WLAN possessing a higher proportion of functions, thus this is a supposition focused on this (Xu et al., 2004). But as laptops are starting to be employed like VoIP and mobiles like laptops, such theories may not look well in the coming days.

Billing on one side and safety on the other are the factors that diminish against the take-up of WLAN or cellular multi-hopping. As nodes possessed by others are transited by the user information, both of them are issues. Thus, the issue of safety and the encouragement or recompensation of users to sustain their involvement who are already in the relay chain arises (George et al., 2008). No real deployments of this function are known despite a lot of fascination.

7.2.3. Communal Networking

A most efficient remedy for an isolated community would be the installation of a single connection and everyone sharing it as it has no broadband connection. The broadband backhaul gets linked to a single mesh node while the meshing of user nodes takes place sans an infrastructure.

In communal networks, there are various instances of ADSL facilities being shared. The facility can be made reasonably priced for isolated societies by using a single mesh for the purpose of sharing a sole pricey internet link such as a leased line or a satellite. If local fascination is high then an outstanding worth of satellite connection or T1 can be provided inside the community as it is usually not within the range of personal users or small businesses (Le et al., 2019).

However, broadband has been serving advanced communities well and this area is not seen as a place for a lot of development. But, in less advanced countries, it has the potential to develop as it has formed a basis there. Hence, this is one of the better instances of mesh utilization.

7.2.4. Office Internal and Home Networking

No infrastructure, need for motion and great bandwidth requirement are all the ways this is alike to WLAN hotspot extension. Probable and innovative mesh-based facilities are discussed by closed user unit transmissions as they are part of the finest features of a mesh (Powell, 2008).

The tide in home networking is not in the course of meshing with an interior, ad hoc focus but IEEE 802.11 is working on it. For supporting concurrent multimedia facilities, greater data frequency is what the tendency is focused on. For instance, a hundred Mbps having lower latency LANs is targeted by 802.11n. Whereas, in the PAN area, great data frequency is being targeted by 802.15.3. Lastly, due to the restricted path of upgradeability, issues of latency, and relay bandwidth issues, this usage is not suitable for mesh (Oksman and Galli, 2009).

7.2.5. User Side Meshing Conclusion

The usage is what the appropriateness of this method relies upon. The advantages and disadvantages will be pointed out for generalization.

Following are the advantages of cellular multi-hopping as previously mentioned (Hayes et al., 2014):

- In ordinary situations, a span extension of about x2 looks attainable. The density of the base station has been greatly reduced becomes apparent. The throughput power of the relay nodes, and the ratio of the access point to node antenna heights and growth, influence the degree to which cell border can be expanded through multi hopping.
- Burdening cellular systems, the link-budget devising room for log-normal fading has been reduced.
- However, the disadvantages of the method are as following (Light and Miskelly, 2019):
- Service extents cannot be ensured by the worker which leads to poor QoS (quality of service); the goal of cellular multi-hop is the decrease of costs through the abolition of infrastructure but its only solution to the problems is to add a proper infrastructure;
- Quality of service will also be influenced by an increase in latency due to multi-hopping.

Thus, the places where working sans an infrastructure is less significant than the importance of coverage and quality of service is where the method of multi-hop is successful. Having a route to a proper power source, immobile relay nodes should be included in the implementation.

7.3. BACKHAUL OR NETWORK SIDE MESH APPLICATIONS

A process generally known as backhaul deals with an operators' need to interconnect the cell sites of any wireless access network with multiple cells to an operating center and consequently, the wider wired network. This requirement exists whether a Wi-Fi hotspot operator or a cellular operator is considered (Boch, 2009).

The emphasis is on the links formed between cell sites giving rise to a mesh rather than meshes being formed by users thus bring forth the term backhaul meshing or network side meshing.

7.3.1. Micro Base Station Backhauls

Micro base station backhaul has been specifically focused on as there are smaller cell sites with plenty of activity known as hotspots, microcells, and picocells. Users demanding increased bandwidth influence smaller cell sites. As mentioned previously WLAN and next-generation cellular solutions are anticipated to be converted into 4G, which are predicted to aid higher bandwidth applications (Sakaguchi et al., 2017).

Presently, 3G networks have smaller cell coverage areas as they are being utilized for higher bandwidth. Smaller cells indicate a greater number of cells being arranged more compactly pointing towards more backhaul. For the satisfaction of consumer demands in the city's numerous high bandwidths, deployments are made. Hence, backhaul can become an important capital expense of the deployment. Installation of backhauls' conventional techniques, like copper or fiber links, is quite expensive in the cities as digging up streets requires an astounding cost per mile, usually up to five figures. Backhaul employs another option of a microwave link approximately 10, 20, or 30 GHz, however, it does not go well with the crowded urban setting (Huang and Psounis, 2019).

Even though mesh nodes call for an increased power supply, a mesh is deemed fitting for backhaul due to its coverage attribute and its independence from the need of conventional infrastructure making it less costly to install in urban settings along with. Lately, wireless cities seem to be a significant driver of interest for the mesh.

7.4. NETWORK SIDE AND JOINT USER MESH APPLICATIONS

As observed with vehicular ad hoc networks (VANETs), network side and user side meshing are not exclusive.

7.4.1. Vehicular Ad Hoc Networks (VANETs)

Several national transport agencies are attracted to move to increasingly intelligent transport systems (ITS) in the coming years. Improved environmental performance, congestion avoidance, and enhanced safety are its three drivers (Zeadally et al., 2012).

Producing an opportunity for mesh structure is a safety feature of ITS. The advantages of enhanced safety organizations are simple to accept; the use of systems that aid drivers in making the correct decisions can lead to lesser deaths on the roads. Stop sign warnings and electronic brake lights (EBL) are two of the most quoted examples. EBL comprise a signal that is given off from a car up ahead to inform the next driver that the car in the front has used its brakes (Zeadally et al., 2012). The system of the second car can even automatically administer the brakes if the first car applied them heavily. This calls for communication between the cars-where there is little tolerance for delay. When an automobile nears a stop sign, it is suitable to receive a warning regarding it. Before the driver can drivers can be warned about the approaching red light before them sensing the upcoming light. Additionally, the system can alert the driver that the vehicle will not be able to stop by the sign until quick action isn't taken considering the present speed. Therefore, communication is demanded among the infrastructure of the roadside and cars, particularly traffic lights in this case (Rehman et al., 2013).

The testing and development of wireless networks which link the transport vehicles and infrastructure, VANETs has been promoted by ITS safety feature. Normally they are divided into roadside-to-vehicle (R2V) designs and car-to-car designs where the car-to-car plans generally require the least latency. EU and USA are drawing near to Japan in experimentation that has been carried out for some time. A range of these services have been made available in the USA and Japan whereas the EU is at the last stage of drafting a harmonized spectrum allocation, this explains the intensity of action and momentum (Martinez et al., 2011).

VANETs can be a mixture of meshes, in which both network side (R2V) and user side (C2C) meshing are acceptable, making it more fascinating. A lot of growth is being anticipated in commercial VANET activity while it is highly likely that legacy communications will also pay attention to the latest transportation prospects. Real-world VANET paradigms will be discussed later on.

7.5. TIME SCALES

Regulatory and technological points of view must be taken into consideration while analyzing time scales for mass mesh authorization. Meanwhile, because of different methods through which meshes function, like user demands of service level aberrations and selfish user effects as mentioned before, there are human factor characteristics as well. It is possibly a 'softer,' user-oriented issue due to which it could be difficult to forecast outcomes on the time scales for mesh approval as a whole. For regulations, the deviation from the command-and-control technique of spectrum organization has anticipated the promotion of innovation. However, as most of the legislation precedes mesh networking approaches, some unforeseen regulatory barriers may require clearing (Speta, 2004).

Hence, factors such as cross-layer protocol cooperation, transport, modeling software, medium access, and routing require development. Normally, the advancement of electronic hardware is not restricting limiting mobile mesh networking (Liu et al., 2006).

If the behavior of users limits the flourishing operation of mesh networks, then ways to alter them are essentially needed (Le and Hossain, 2008). It is rather complex to quantify such an undertaking. Respective time scales for different factors of innovation are described in Figure 7.4.

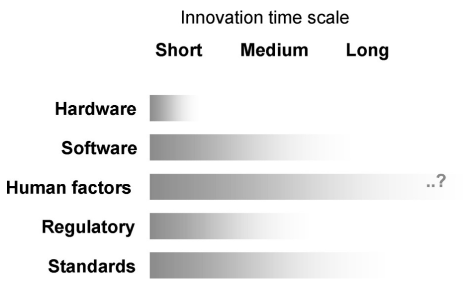


Figure 7.4. Mesh adoption (predictions)'s time scales.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/0DE3EF74BA5FEE59999B18001B4293B0.

REFERENCES

1. Alam, M., Khan, A. H., & Khan, I. R., (2016). Swarm intelligence in MANETs: a survey. *Int. J. Emerg. Res. Manag. Technol.*, *5*(5), 141–150.
2. Alotaibi, E., & Mukherjee, B., (2012). A survey on routing algorithms for wireless ad-hoc and mesh networks. *Computer Networks*, *56*(2), 940–965.
3. Altieri, A., Vega, L. R., Piantanida, P., & Galarza, C. G., (2013). Analysis of a cooperative strategy for a large decentralized wireless network. *IEEE/ACM Transactions on Networking*, *22*(4), 1039–1051.
4. Behnad, A., Rabiei, A. M., Beaulieu, N. C., & Hajizadeh, H., (2013). Generalized analysis of dual-hop DF opportunistic relaying with randomly distributed relays. *IEEE Communications Letters*, *17*(6), 1057–1060.
5. Boch, E., (2009). High-capacity ethernet backhaul radio systems for advanced mobile data networks [application notes]. *IEEE Microwave Magazine*, *10*(5), 108–114.
6. Chen, J., (2006). The echoes of forgotten footfalls: Telecommunications mergers at the dawn of the digital millennium. *Hous. L. Rev.*, *43*, 1311.
7. Chen, W., Dai, L., Letaief, K. B., & Cao, Z., (2008). A unified cross-layer framework for resource allocation in cooperative networks. *IEEE Transactions on Wireless Communications*, *7*(8), 3000–3012.
8. Cooper, M., (2000). Open access to the broadband internet: Technical and economic discrimination in closed, proprietary networks. *U. Colo. L. Rev.*, *71*, 1011.
9. Dan, A. O., Xu-Ming, F. A. N. G., & Zhong-Jian, M. A., (2005). Key technology and applications of wireless mesh networks [J]. *Telecommunication Engineering*, *2*, 16–22.
10. de Renesse, R., Friderikos, V., & Aghvami, H., (2007). Cross-layer cooperation for accurate admission control decisions in mobile ad hoc networks. *IET Communications*, *1*(4), 577–586.
11. Deepalakshmi, P., & Radhakrishnan, S., (2014). An ant colony-based, receiver-initiated multicast mesh protocol for collaborative applications of mobile ad hoc networks. *Transactions on Emerging Telecommunications Technologies*, *25*(3), 354–369.

12. Ganti, R. K., & Haenggi, M., (2012). Spatial analysis of opportunistic downlink relaying in a two-hop cellular system. *IEEE Transactions on Communications*, *60*(5), 1443–1450.
13. George, A., Kumar, A., Cavalcanti, D., & Agrawal, D. P., (2008). Protocols for mobility management in heterogeneous multi-hop wireless networks. *Pervasive and Mobile Computing*, *4*(1), 92–116.
14. Hayes, B., Hernando-Gil, I., Collin, A., Harrison, G., & Djokić, S., (2014). Optimal power flow for maximizing network benefits from demand-side management. *IEEE Transactions on Power Systems*, *29*(4), 1739–1747.
15. Hongqi, J., Kai, K., & Xiaokang, L., (2005). Wireless mesh network extending broadband access [J]. *Telecommunications Science*, *1, 4–10*.
16. Huang, P. H., & Psounis, K., (2019). Optimal backhauling for dense small-cell deployments using mmWave links. *Computer Communications*, *138*, 32–44.
17. Hundt, R. E., & Rosston, G. L., (2006). Communications policy for 2006 and beyond. *Fed. Comm. LJ*, *58*, 1.
18. Khan, K., & Akbar, M., (2006). Authentication in multi-hop wireless mesh networks. *Transactions on Engineering, Computing, and Technology*, *16*, 178–183.
19. Le, L., & Hossain, E., (2008). Cross-layer optimization frameworks for multihop wireless networks using cooperative diversity. *IEEE Transactions on Wireless Communications*, *7*(7), 2592–2602.
20. Le, M., Clyde, S., & Kwon, Y. W., (2019). Enabling multi-hop remote method invocation in device-to-device networks. *Human-Centric Computing and Information Sciences*, *9*(1), 1–22.
21. Lemley, M. A., & Lessig, L., (2000). The end of end-to-end: Preserving the architecture of the internet in the broadband era. *Ucla L. Rev.*, *48*, 925.
22. Light, A., & Miskelly, C., (2019). Platforms, scales, and networks: Meshing a local sustainable sharing economy. *Computer Supported Cooperative Work (CSCW)*, *28*(3), 591–626.
23. Lin, Y., & Wong, V. W., (2008). An admission control algorithm for multi-hop 802.11 e-based WLANs. *Computer Communications*, *31*(14), 3510–3520.

24. Liu, P., Tao, Z., Lin, Z., Erkip, E., & Panwar, S., (2006). Cooperative wireless communications: A cross-layer approach. *IEEE Wireless Communications*, *13*(4), 84–92.
25. Mahajan, R., Singh, S., Bhardwaj, A. K., & Sharma, P., (2013). Trust based routing for secure wireless networking solutions. *International Journal of Advanced Research in Computer Science and Software Engineering*, *3*(8), 14.
26. Martinez, F. J., Toh, C. K., Cano, J. C., Calafate, C. T., & Manzoni, P., (2011). A survey and comparative study of simulators for vehicular ad hoc networks (VANETs). *Wireless Communications and Mobile Computing*, *11*(7), 813–828.
27. Oksman, V., & Galli, S., (2009). G. hn: The new ITU-T home networking standard. *IEEE Communications Magazine*, *47*(10), 138–145.
28. Powell, A., (2008). WiFi publics: producing community and technology. *Information, Communication & Society*, *11*(8), 1068–1088.
29. Rehman, S., Khan, M. A., Zia, T. A., & Zheng, L., (2013). Vehicular ad-hoc networks (VANETs): An overview and challenges. *Journal of Wireless Networking and Communications*, *3*(3), 29–38.
30. Sakaguchi, K., Haustein, T., Barbarossa, S., Strinati, E. C., Clemente, A., Destino, G., & Heath, Jr. R. W., (2017). Where, when, and how wave is used in 5G and beyond. *IEICE Transactions on Electronics*, *100*(10), 790–808.
31. Shelanski, H. A., (2007). Adjusting regulation to competition: Toward a new model for US telecommunications policy. *Yale J. on Reg.*, *24*, 55.
32. Speta, J. B., (2004). Dregulating Telecommunications in Internet Time. *Wash., & Lee L. Rev.*, *61*, 1063.
33. Weiser, P. J., (2003). Toward a next generation regulatory strategy. *Loy. U. Chi. LJ*, *35*, 41.
34. Xiaoyu, F. Z. W. S. W., & Bingjun, L., (2004). Survivability of next generation optical transport mesh network [J]. *Modern Science & Technology of Telecommunications*, *2,* 15–20.
35. Xu, S., Papavassiliou, S., & Narayanan, S., (2004). Layer-2 multi-hop IEEE 802.11 architecture: Design and performance analysis. *IEE Proceedings-Communications*, *151*(5), 460–466.

36. Xu, Y., Wu, P., Ding, L., & Shen, L., (2011). Capacity analysis of selection cooperation in wireless ad-hoc networks. *IEEE Communications Letters*, *15*(11), 1212–1214.
37. Zeadally, S., Hunt, R., Chen, Y. S., Irwin, A., & Hassan, A., (2012). Vehicular ad hoc networks (VANETS): Status, results, and challenges. *Telecommunication Systems*, *50*(4), 217–241.
38. Zhai, C., Zhang, W., & Mao, G., (2012). Uncoordinated cooperative communications with spatially random relays. *IEEE Transactions on Wireless Communications*, *11*(9), 3126–3135.
39. Zhang, R. Z., Yu, S. J., Bai, H., & Ning, K., (2017). TCM-Mesh: The database and analytical system for network pharmacology analysis for TCM preparations. *Scientific Reports*, *7*(1), 1–14.
40. Zhou, Y., & Zhuang, W., (2017). Opportunistic cooperation in wireless ad hoc networks with interference correlation. *Peer-to-Peer Networking and Applications*, *10*(1), 238–252.

Chapter 8

Mesh Networks of Wireless Sensor Networks (WSNs)

CONTENTS

8.1. INTRODUCTION

Let us start with the wireless sensor networks (WSNs) overview. We took relatively a comprehensive overview earlier to focus on the networking features of WSNs.

The function of a wireless sensor network is significantly similar to a monitor. Normally speaking, what is being observed could usually be positioned in any of three groups (García et al., 2009; Singh et al., 2010):

- Entity monitoring: for example. monitoring something; instances comprise a human body or a civil structure (building, etc.);
- Area monitoring: for example, monitoring somewhere; instances comprise the area alarms (intrusion, etc.), or environment; and
- Area entity interaction monitoring: for example. monitoring somewhere, something, in perspective; instances comprise automobiles on the road, tracking of an asset, or the movement of a manufacturing procedure.

Why a sensor network is significant, is understood through realizing that, regularly, distinct sensors themselves are restricted in their capacity for monitoring a given condition. Precisely, a particular sensor is not probably to embody adequate scope to sense a whole phenomenon alone, neither the dependability on the system is expected to be very good, as the sensor shows a single point of a letdown. The technique of communicating the subsequent information to a base unit might also bring challenges to a system (Figure 8.1) (Liu et al., 2009).

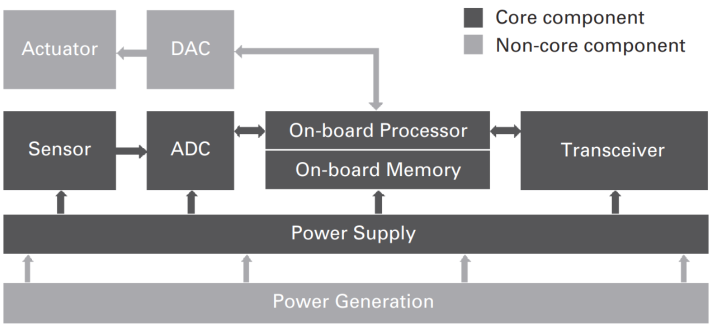


Figure 8.1. Block diagram of a basic WSN mote.

Source: https://www.semanticscholar.org/paper/Design-of-miniaturized-wireless-sensor-mote-and-for-Jafer-O%27Flynn/77cca5cc2d1d70484ad93116bbbcb6c5adec79ac/figure/0.

The sensor network strength derives from the fact that although the distinct nodes are quite restricted when networked the entire array becomes very influential. Therefore, sensor networks are probably to be huge in scale, that they had numerous nodes in the sense and they probably to be self-configuring, to bring dependability. Similarly, the nodes themselves are probably to be economical, like those numerous nodes might be economically deployed. In this section, we would introduce (Bose and Morin, 2004):

- Harvesting and power sources;
- Differences amongst mesh, RFID, and WSN;
- Interfacing and sensing technologies;
- Key WSN standards exertions; and
- The structure question in WSNs.

We would conclude through drawing parallels amongst sensor networks and mesh, however, first, let us see what creates up a node of the wireless sensor (Bose et al., 2013).

8.2. WIRELESS SENSOR NODE COMPONENTS

A concrete wireless sensor node must comprise of at least the following (Karray et al., 2018):

- A sensor, for example. a light sensor or a MEMS (microelectromechanical system) accelerometer;
- Memory and processor, of marginal power needs;
- A signal converter, for example, an analog to digital converter;
- A wireless network interface, for example, optical or radio; and
- A power supply, or a technique of harvesting power, for example from light or vibration.

The word ‘mote’ is generally used to explain a node, rather than without or with its related sensors. It is exciting to note that the definition of a mote is a ‘speck of dust from the dictionary, or similarly, and this explains the function of diverse sensor nodes very fine. Each is comparatively little, like a speck of dust, however, in the network, there are many specks of dust (Mascarenas et al., 2007).

A main theme of motes is that they are required to be self-powered or low power, as that they might last for numerous years in situ, without the inconvenience of maintenance and suffering the cost. This low power theme motivates much of our explanation in this section.

Let us start by allowing the transducer, that is the very 'front end' of the sensor node, the portion which observers the phenomenon property to be sensed and transforms it into a certain electronic type (Pughat and Sharma, 2017).

8.3. WSN SENSORS

Sensors might be grouped is through their major operating principle as follows (Hussian et al., 2013):

- Thermal sensors;
- Optical, acoustic, and electromagnetic, sensors;
- Physical sensors;
- Biological and chemical sensors.

We would not discuss all the sensors now, however, we would point out that there had been numerous progress in sensors in latest years.

One instance is the latest development in integrating sensors on the silicon, which is the turning point for the incorporated devices. Instances are gyroscopes and MEMS accelerometers. These came under the description of integrated iMEMS or MEMS, and are value a distinct mention (Srbinovski et al., 2016).

Though a MEMS device near to its related electronics passes operational gains and decreases the cost, particularly if the electronics and sensor are on a similar silicon procedure. An instance device that comprises capacitance and piezo principles and which has incorporated electronics is the iMEMS gyro. or nano-gyro.

The device's significance is not that it is a novel concept, as gyros had been around for numerous years. Its significance lies in the point that this device is currently reasonable to assist many extra applications. For instance, rather than depend on GPS only to assist navigate vehicles, an iMEMS gyro could give inertial navigation. This could be economical than GPS and to function where GPS can't, where the GPS satellite's view is jammed. It also couldn't be blocked in the similar way that GPS could (Ding et al., 2015; Rani et al., 2017).

8.4. WSN POWER SOURCES

Firm power consumption needs come from the requirement for the sensor node to be autonomous and able of working unattended for a long period, possibly for numerous years. WSN lose their hold if expensive maintenance visits had to be done, for instance for batteries replacement. Variables in the design comprise (Mishra and Thakkar, 2012):

- The selection of power harvesting schemes or battery;
- Little power electronic design methods.

The power sources are generally divided into primary and secondary cells, the main difference is that primary cells by design, can't be recharged, however, secondary cells had a necessity for consistent charging. The main parameters of primary and secondary cells comprise temperature range, existing drain level, capacity, and self-discharge features. Otherwise, there is also a storing method founded on capacitors, termed supercapacitors. Whereas these are firmly not power cells, they are beneficial energy stores. A probable prospective energy source is fuel cells if they might be created little and enough safe for further applications (Castagnetti et al., 2012).

8.5. WIRELESS SENSOR TECHNOLOGIES AND APPLICATIONS

In this part, we would see what other things at the physical level need to be provided so that we might continue to utilize sensors simply in applications, for example, what are the remaining technical enablers. This leads to TEDS (transducer electronic data sheets) (Wang et al., 2013).

8.6. DIFFERENTIATING RFID, MESH, AND SENSOR NETWORKS

It is beneficial to be known of the differences between mesh networks and WSNs. RFID is also of main interest because of its expected future growth, which might take it into the territory of Wireless sensor technologies (Callaghan et al., 2006).

Let us start by comparing, as directly as probable, the various features of RFID, mesh, and WSN network nodes as they occur currently.

8.6.1. RFID

RFID is utilized for tracking assets and remote keyless entry or car immobilizers. RFID stands only in that it is proposed for the lowermost cost, even factually throw away applications also it has not functioned as a network. It is said that in actuality there are 4 probable classes of RFID, with the lower classes being impressively more usual currently, and so creating the comparison basis. The 4 classes are as follows (Weinstein, 2005; Juels, 2006):

- **Passive RFID:** It had no built-in power source. It depends on backscatter and the only single device could be read once in the scanner field. Though, it is frequently said that several of these devices could be 'simultaneously' read through a single scanner several devices are read serially utilizing a back-off algorithm. This is the most economical tag, utilized to prevent theft and for the item ID.
- **Semi-Passive RFID:** It had a built-in power source for usage in processing and through other peripherals, possibly sensors, however, the power source is not utilized for the transceiver and thus does not increase range. It is also a backscatter-type tag. This form of a tag is utilized in road tolling schemes, for instance, the novel bridge at Dartford over the River Thames.
- **Semi-Active RFID:** It had a power source which is accessible to the transceiver also for everything else. Though the node is predicted to sleep for most of the time, for example, it had a low duty cycle. The tag is able of starting communication, which makes it quite dissimilar to the passive tags (Weinstein, 2005).
- **Active RFID:** It is powered and the transceiver could be constantly on, which could form it somewhat like a WSN node. To evade doubt, note that we had taken out active RFID from prospects on the grounds of keeping simplicity for this contrast. Active RFID is the next generation of RFID and much more influential than the RFID mostly industry is aware with it currently. Active RFID could be very skilled and could become vague from a WSN in an application. We, therefore, expect WSN and active RFID applications to come together (Want, 2006).

8.6.2. Mesh Networks

We had previously shown mesh applications which currently comprise municipal wireless roll-outs and, in the upcoming, we assume VANETs (vehicle ad hoc networks) to be a huge application.

Full movement is a large differentiator of mesh networks from WSNs or RFID. A huge radio range goes hand in hand. This huge range, collected with the performance levels projected through the applications, suggest a good battery would be needed. And if required this battery could be recharged every day, as the environment's application assists this. Power source and range are therefore very diverse for mesh networks when matched to both RFID and WSN (Akyildiz et al., 2005).

Previously in the book, we observed that extra network infrastructure could be utilized to enhance the quality of service and scalability for mesh networks. We would show that this result carries over to Wireless sensor technologies.

8.6.3. Wireless Sensor Networks (WSNs)

Environmental, logistics, smart buildings, and industrial monitoring are the most generally mentioned applications for Wireless sensor technologies (Akyildiz and Wang, 2005).

Huge differentiators of WSN from mesh are the restricted data ability and the related power savings. On average, WSNs might need only a few bits per second per day. WSNs do not carry actual-time streaming facilities, neither are they utilized where latency is crucial. In other words, WSNs are neither video nor even capable of voice, though people had tried VoIP over 802.15.4 with restricted success. The largest source of power saving of WSNs is their little duty cycle, fewer than 1%.

We would look more strictly at necessities for WSNs in Section 10.8, however, we must relate WSNs to mesh networks to create the main similarities and differences at the biggest level (Akyildiz et al., 2002).

8.6.4. Comparisons Between Mesh and Sensor Networks

Placing RFID entirely aside, let us now list the resemblances and variances amongst mesh and sensor networks. These are as following (Khan et al., 2020):

- Having economical WSN nodes perhaps means having fewer reliable nodes than mesh networks;
- WSNs comprise further nodes at a greater density, also the radio range is lesser. WSN traffic is lesser complicated, definitely not real-time, and bit rates might be merely some bits per day;
- Wireless sensor networks traffic is a very specific application, and the design of nodes might follow this, creating nodes fixed;
- Wireless sensor networks could contain also sensors as well.

- An extra beneficial understanding is that whilst the directing challenge for wireless mesh networks (WMNs) is managing with mobility, the WSNs directing challenge is handling with restricted energy (Ferrari et al., 2007).
- There are also resemblances amongst mesh and sensor networks:
- Both have security challenges;
- Both are self-forming networks;
- Both have privacy challenges;
- Both, in principle, do not require infrastructure;
- Both, in exercise, assist from infrastructure. The mesh gains from access points to enhance QoS as we had shown in previous chapters, and the WSNs from gateways/routers to enhance power consumption for edge nodes edge, also we should show in this chapter;
- Both, in actuality, gain from gathering to cheat scalability problems;
- Both present reliance of the network on the behavior of the node.

It is valuable to recall that both are cooperative networking methods, through which we say that medium access regulator is decentralized and there is an element of reasonable argument for resources included for every node. It means that these systems should co-exist also probable with one another, however, that other structures functioning centralized medium access might lead. In other words, sensor networks and mesh usually run polite protocols and might suffer when co-located with structures functioning impolite protocols (Ye et al., 2005; Waharte et al., 2006).

8.7. DIFFERENTIATING 802.15.X, ZIGBEE, AND 6 LOWPAN

There are huge many acronyms for defacto and ad hoc standards in usage in the field of WSNs (Figure 8.2).

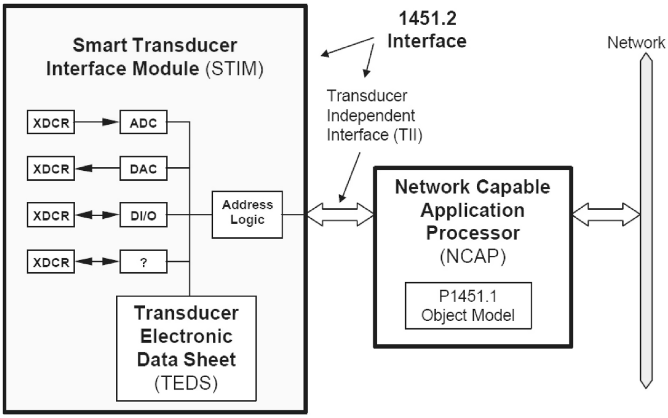


Figure 8.2. IEEE 1451 functional diagram.

Source: https://www.researchgate.net/figure/The-IEEE-1451-Standard-for-smart-Sensor-Networks_fig1_226113217.

Figure 8.3 shows a rather basic stack, however, is adequate to show the general layer-level split we have defined. The word 'academic' mentions to university research networks that frequently use 802.15.4 as the examinations base of the upper levels, like as routing algorithms (Raptis et al., 2020).

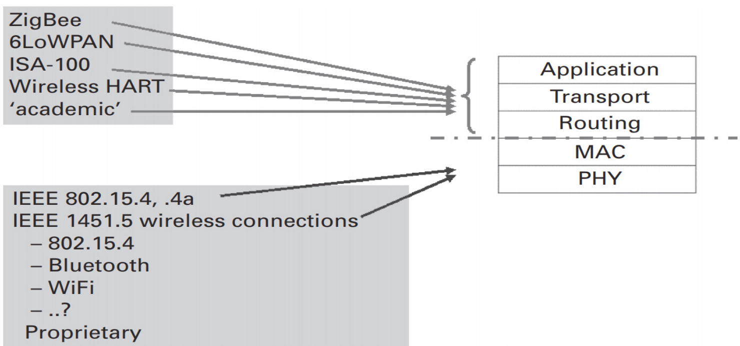


Figure 8.3. Standards and anywhere they fit.

Source: https://www.researchgate.net/publication/290301763_Essentials_of_wireless_mesh_networking.

8.8. A SUGGESTED TAXONOMY OF WSNS: STRUCTURE AND EQUALITY

There is a huge deal of data in the literature regarding WSNs, it is useful to form a basic taxonomy to evade confusion. We had found, similarly, we do with mesh networks, that the existence of structure, like a node hierarchy or a wired infrastructure, makes a great deal of difference in the performance of the network. Network performance and design are both significantly different when the network had structure related to when it doesn't (Abbasi and Younis, 2007).

On a correlated, however, different note, a similar situation could be created for the equality of node. When altogether nodes are like, the network design moves contrarily to when certain nodes have unsatisfactory performance. This dissimilarity could be for worse or better, for instance, anode with influential processing capability vs a node which could occur only on scavenged power. There are obvious benefits to having nodes with inadequate capability, generally, only these nodes are required to be specialized, leaving others to be fewer complicated and therefore less power required. Thus, our basic taxonomy is founded on the concepts of * node equality and network structure (Zeb et al., 2016).

8.9. SYSTEM ARCHITECTURE IN SENSOR NETWORKS

In this portion, we would review WSN's needs from a system design point of opinion. We follow this through seeing how the Internet is typically organized utilizing the TCP/IP suite and take out some contrasts. Taking these 2 features together permits us to inspect the comparative applicability and appropriateness initially of unstructured WSNs and later on structured WSNs. This ultimately takes also into a conversation on the equality of nodes, where we utilize 802.15.4 as a specific instance of a structured network with diverse types of nodes. The ideas of network structure and node equality are connected; however, the idea of node equality is wider than network structure. There are several other techniques in which nodes could be made inadequate, like as performing as security centers, offering translating gateways, or generally being more powerful in computing terms, which often also shows access to a capable power supply (Fuentes et al., 2009).

8.10. UNSTRUCTURED WSNS

In distinction to structured methods, unstructured networks are similar to node form and therefore have no physical hierarchy. An additional method of saying this is that all nodes are equivalent, architecturally, and physically (Lee et al., 2012).

In an unstructured WSN, the sensors had no mechanism for out-of-band communication or control-all communication is through their single wireless communication interface.

Once deployed, unless there is a very carefully managed deployment with careful pre-configuration of the sensor nodes must perform all of the following tasks:

- Locate/discover other sensor nodes in their network;
- Discover a route back to the gateways or sinks, the points in the network at which the collected information must be presented, perhaps for onwards transmission beyond the sensor network;
- Forward relevant data towards the gateways or sinks using the other sensor nodes as relays;
- Maintain/update routes to the gateways or sinks in the case of a node failure, nodes, and/or gateway/sink mobility, and/or due to other policy requirements, for example, network load sharing, conservation of power across sensor nodes through diverse routing, etc. (Lee et al., 2012).

Such networks and related technical issues are often the focus of academic and military research. Typically, the approach taken is to use ad hoc networking, with the additional constraint of resource limitation. This additional limitation could take the form of any combination of limits on network capacity, CPU power, memory, battery life, etc. In this way, the WSN challenge becomes greater than the ad-hoc networking challenge (Lee, 2017).

Unstructured WSNs are often thought to have the attribute of lowest power operation, usually, because they have been designed to be so application-specific that all unnecessary functionality is simply not included. If we compare this with a structured WSN, whereas the gateway node(s) might be mains powered, the real sensor nodes could be very less power, as they might not have a similar level of obligation for giving functions like as network time synchronization, localization, routing, data filtering, and localization (Nayyar and Singh, 2019). The major drawback with structured networks is generally the Ad hoc feature and mobility are lost possibly lost. In other words, less power only is not certainly a driver for an unstructured method, and it might be that further factors, like the ability to be mobile, are significant enough that the entire system design is amended so that other limitations are given lesser importance.

On the other side, it emerges that various probable applications of the unstructured WSNs are not in actual mobile; however, the convenience of an unstructured method not had to organize and hold a 'backbone' for the nodes of the sensor network to sinks/gateways are simply better. The benefits and balance of costs would differ from application to application (Chugh and Panda, 2019).

In each case, we had to deal with general functions of communication like routing, addressing, data transfer, discovery, and route maintenance, comprising robustness to the letdown of nodes also alteration of topology through mobility.

Now we look at how routing might be organized, particularly for the situation of the unstructured WSN, through three methods: geographic routing, data-centric routing, and other techniques comprising energy-aware routing. All are fairly different from the traditional IP addressing which we previously reviewed (Raja et al., 2015).

8.10.1. WSN Approaches: Data-Centric Routing

After the argument given at the last of Section 10.8.2, a precise application founded on a sensor network might be more anxious with the type of the data from the sensor field relatively than the routing or addressing information. That is why a paradigm suggested for transmitting in sensor networks, which uses a data-centric method to routing and distribution of data through the sensor nodes, regardless of an address-based method. One of the most mentioned works in this area explains directed diffusion (Krishnamachari et al., 2002), and this provides a very good explanation of the principle of a data-centric method.

The general principle rises from seeing the user motivation of a sensor network, who is involved in data and hence would like replies to questions like as 'How many types A events happened in area X?' Such an inquiry would be forwarded to the sensor network and we would say that sensors had been tasked through collecting data to reply to the query. Co-operation is then made by nodes to 'reply to the question' and provide the outcome to the user. For enabling this in a robust, energy-effective, and scalable manner, the paper suggests the usage of routing utilizing attribute-value pairs to term data that are produced through sensor nodes (Krishnamachari et al., 2002). It is noted that the data are termed and not the nodes by themselves. Through diffusing (sending interests for) or advertising, the termed data to its neighbors, the data gathered through nodes are tired towards the node that produced the term. Intermediate nodes could utilize the name to start caching, execute data aggregation, forward stored/historic outcomes, or forward novel outcomes matching that name to the basis of the name (Boukerche et al., 2005).

Summarized, the common principle is that the information of the data needed by sensors, as promoted in their benefits, permits their neighbors to send data properly. The selection of the sink (the node that produced the interest) is random. The sink occasionally transmits its interest(s) requirement and its neighbors keep an interests reserve. If previously the interest is not existing in the cache, the node which is receiving register the interest in the cache and the node from where it is generated, and then forward the message of interest to its neighbors. Through this method, a 'gradient' is made directing back to the source, specifying the data flow path to the sink that showed the interest (Karthikeyan and Kavitha, 2013).

However, data-centric routing is far away from the only choice, as we observe in the following two sections (Figure 8.4) (Zabin et al., 2008).

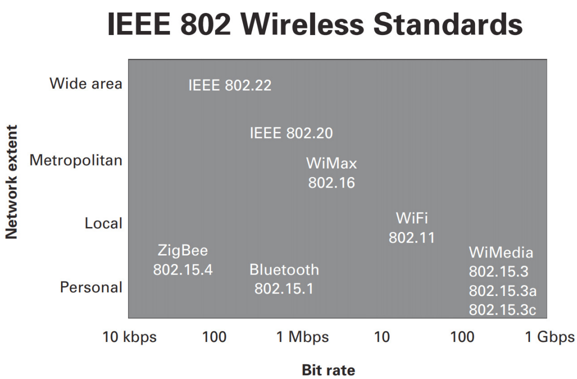


Figure 8.4. Radio (PHY/MAC) contrast.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/wireless-sensor-networks-wsns-as-mesh-networks/9E3F79AC60B60BB945CCE9077C18C1E3.

8.10.2. WSN Approaches: Geographic Routing

The positioning of a sensor network in the real world, it is obvious from our previous discussion that location, for example, geography, is significant for several applications. We noticed that even for the instance of the data-centric method above, events, and sensor nodes have certain location information that is significant for the application. Thus, it appears natural to consider geographic or location information as candidates for sensor network routing (Zhang and Shen, 2009).

Once again, we take as our instance one of the most-cited functions in the field, which in this situation is the one of GPSR (greedy perimeter stateless routing). The general principle of GPSR shows the simple principle of geographic or location routing basically that we should constantly forward packets to nodes that become closer (geographically) to their endpoint. In Figure 8.5, we saw the source and its future destination. In the greedy method, the source constantly utilizes the node that is inside the radio range and nearest to the endpoint. In this situation, it is the shaded node. This procedure of choosing the forwarding node lasts till the packet reaches its endpoint. Several refinements might be added to the technique to overwhelmed obstacles like local maxima (Denardin et al., 2011; Huang et al., 2107).

The principal benefit of geographic routing is that a node required information regarding only its instant neighbors, as decisions of forwarding are made on the data of the location of the neighbors and the destination.

Though, geographic routing in this method needs the existence of a secure and influential source of location data, and a mechanism (e.g., a secure server) that would give mapping amongst node addresses and locations so that packets could be transferred on to neighboring nodes (Petrioli et al., 2013).

8.10.3. WSN Approaches: Other Routing Mechanisms

Geographic and Data-centric methods are not merely mechanisms under deliberation for routing in unstructured WSNs. Huge amount of literature linking to energy-efficient routing or energy-aware. This is intended to take into account the usage of valued battery power which outcomes from packet forwarding. Several strategies can be utilized for the conservation of energy (Deebak and Al-Turjman, 2020):

- Conservation of energy for the network entirely through load distribution, for instance, multi-path routing, to evade draining batteries on a particular path. This might be executed by discovering high-energy nodes and utilizing those first.
- Regulating transmission power so that only adequate energy is utilized for the transmission to the extent to recognized neighbors.
- Optimization of power-down/idle state/sleep of a sensor node for the conservation energy. This choice is previously used to some degree in generally WSNs.

The significance of energy conservation of energy would vary relying on the application. Certainly, the several approaches (geographic, energy-aware, data-centric,) try to optimize for a precise network situation, and thus they might not be suitable for the general situation. Transferring to the general case is complex, for several reasons (Deebak and Al-Turjman, 2020):

- The parameter numbers in a mobile network and their extent of probable values, joined with possible diverse traffic models, diverse failure systems, radio ranges, MAC protocols, node densities, and diverse mobility models, for instance, means that the issue space is very complicated.
- The complication of the situation means that networks are comparatively rarely built, and considerable evaluation work is executed under simulation. It is not obvious that the research community had a comprehensive agreement on simulation situations and how simulations should be performed (Shamsan et al., 2014).

In outline, we think that energy-aware routing is not yet appropriate for the execution stage. Let us consider WSNs where organization and structure are permitted.

8.11. STRUCTURED WSNS

To demonstrate the structured WSN we might yet again borrow from the mesh figures in Chapter 2. The structured WSN might have an internal structure as revealed in figures in Chapter 2, or more probably it would have both structure and a path to reach the WSN, similar to the access mesh.

To assist this observation, and in comparison, to unstructured methods, structured WSNs are frequently the emphasis of standards and industry activity. Now, mobility requirements are low, usually zero, however, interoperability, and flexibility requirements are high. For extensive industrial positioning, the wireless sensor network must be perceived to be dependable and relaxed to work with and the formation of a standard is frequently the best method forward in this situation (Kumar et al., 2018).

8.11.1. WSN Approaches-Hierarchical

Earlier we move in detail, let us examine certain general features of the hierarchical method, general to WSNs. There are numerous reasons why hierarchical networks had been chosen, historically (Figure 8.5) (Zhang et al., 2015):

- Hierarchical routing is proficiently attained;
- Supernodes could take the functioning load off regular nodes;

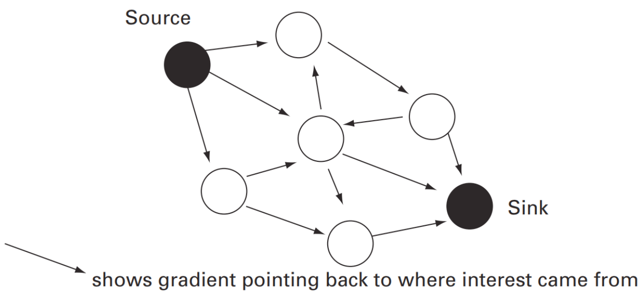


Figure 8.5. 802.15.4-star configuration.

Source: http://ecee.colorado.edu/~liue/teaching/comm_standards/2010F_802.15/home.html.

- Supernodes could direct traffic off the network most rapidly (this decreases hop count and enhance throughput); and
- Security also initiatives a hierarchical method through trust centers.

As an earlier debated structure in this segment, we would also come across the idea that not entire nodes are required to be identical. Hierarchy is linked, however, not equivalent, to the idea that not entire nodes are required to be equal, and that there are various benefits of inequality, like as huge processors for routing information and storing, gateways to the external world comprising the Internet, and entrance to higher power supplies (El-Alami and Najid, 2019). Let us inspect structured approaches through convenient and related instances.

8.11.2. Structured versus Unstructured

We could see at structured vs unstructured methods through taking the instances of 802.15.4, as this comprises choices to produce either form of network. In actuality IEEE 802.15.4 does not identify the configurations, however, does supply a MAC and PHY which are able of being configured so, normally by ZigBee (Deutsch, 1980).

The first three instances are the star network, exposed in Figure 8.6. This is the simplest configuration, which also gives the lowest most latency, through canceling multi-hopping.

Two kinds of devices are revealed in the figure and are defined as follows. The FFD (full function device) is the more proficient device and could achieve any network purpose; the RFD (reduced function device) is much simpler (economical) and could occur only as a final device. Put marginally contrarily, the FFD could talk to any further device, while the RFD could talk merely to the FFD, which is its shortest parent in the hierarchy. Instar or any further configuration, the mostly child nodes an FFD could assist is 254-this contacts very favorable to Bluetooth's edge of only seven slaves (Wethington and McDarby, 2015).

In any 802.15.4 PAN (personal area network), Anyone of the FFDs must choose itself as the PAN coordinator. This then had several tasks. For instance, it must choose a free channel at initiating-up, it must control address allocation, it should manage beacons where they are utilized, it must work as the connection to other networks, if one is required then is a need for one, it must function as the trust center to co-ordinate security, comprising cryptographic key distribution, where this is generally used. Usually, the mains powered is the PAN coordinator. FFDs that are not the PAN coordinator would function as routers in those PANs which are more complicated than the star. Previously we could saw a link between system hierarchy and node equality, which goes a far route, for example, the pull in this situation for certain nodes to be major powered (Stasser et al., 1989; Chowdhury et al., 1998).

Multiple instances of stars are completely independent of each other. A useful comparison is that the star is no more than the access point architecture of 802.11 and it could be expanded by adding wired infrastructure, just as with 802.11. However, 802.15.4 can be more capable than this in the wireless domain alone, as our second of three examples shows.

The most flexible and complex approach is the mesh or peer-to-peer network as it is termed in 802.15.4, as shown in Figure 8.6. In contrast to all other network options the mesh, as shown, is an unstructured network, i.e., it is having a flat hierarchy. Whilst it would be possible to terminate the mesh with RFDs at the edge, this would curtail the possibility for mesh expansion beyond these devices since they are incapable of acting as routers. As one of the main attractions for mesh is its ad hoc expansion, this would be an unusual step, unless a specific application clearly demanded it. Hence, we shall assume that the mesh is most attractive when populated in the main by FFDs to realize its full performance (Bartko and Eccles, 2003).

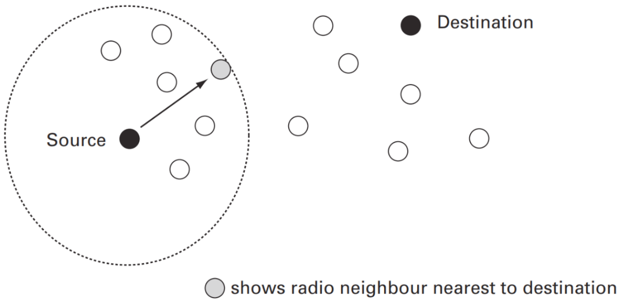


Figure 8.6. 802.15.4 mesh (peer-to-peer) configuration.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/wireless-sensor-networks-wsns-as-mesh-networks/9E3F79AC60B60BB945CCE9077C18C1E3.

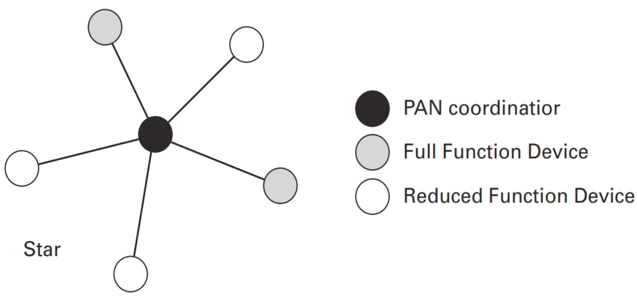


Figure 8.7. 802.15.4 cluster tree configuration.

Source: https://www.wikiwand.com/en/IEEE_802.15.4.

The principal advantages of the mesh are:

- Good and flexible coverage which can be extended simply by adding more nodes without any planning required; and

- Redundancy due to the potential for multipath routing.

Since the mesh has no hierarchy, any node can communicate with any other node which is in range. This makes medium access most conveniently implemented by a contention-based scheme. 802.15.4 offers the option of CSMA/CA. There is also a slotted version of CSMA/CA, supported by beacons generated from the PAN coordinator, but this fits better with stars and the last of our three examples, the cluster tree, shown in Figure 8.7. The reason for this is that propagating beacon information, which is time-sensitive, will become increasingly difficult across a larger mesh (Baars and Kemper, 2008).

The cluster tree has structure, but it represents a compromise between the simple star and the complex mesh, since it is quite flexible, but has simplified routing. It is also lower cost than the mesh since the use of RFDs as end nodes are expected. This does involve an element of planning the deployment. Usually, cluster heads are mains powered and end nodes are battery-powered (Jourdan et al., 2008).

Routing in the star and the cluster tree works a little like the hierarchical approach of IP, as we showed earlier in this chapter. The node addresses similarly contain both identification and location information. A node in the cluster tree determines routing information directly from the destination node address. In contrast, in the mesh, AODV is used, which is a more complicated protocol.

8.11.3. ZigBee/802.15.4 Configuration

Common to all three network architectures is the need to configure the system. One choice to make is the network architecture itself, and the other key choice is whether to use beacons or not.

With respect to architecture, two key parameters can be set to influence how the network will automatically build its topology. These are the maximum network depth and the maximum number of routers (devices which are FFDs, but excluding the PAN coordinator). For example, to create a star, the network depth can be set at 1 and the number of routers can be set at 0 (Casilari et al., 2010).

In architectures other than the mesh, which typically does not use beacons, the choice of whether to use beacons or not comes down to the application needs. If the application is driven by the timeliness of communication, such as a wireless mouse requiring regular communication, then it is most convenient to use beacons. If the application is event-driven, such as a monitoring application, then non-beaconing may be more appropriate. Note that the use of beacons can enable longer sleep modes for suitable periodic applications and so conserve power better (Ott, 2012).

The foregoing has illustrated that adopting network structure can dictate that node inequality, i.e., diversity, should also exist, but that node diversity can go far beyond the network level. We examine node inequality as distinct from hierarchy next.

8.11.4. All Nodes Equal versus Unequal

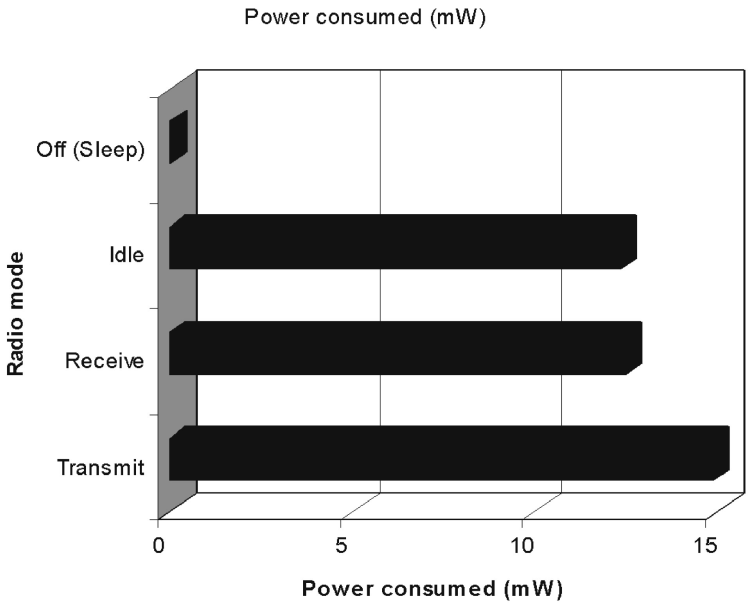
Apart from inequality in the wireless routing functionality as discussed above, nodes may also be deliberately chosen to be unequal in other ways. This includes, for example, their access to power, their processing ability, and their extra network connections, for example to the wired network.

As we have stressed, WSNs are power constrained. However, if we allow inequality of nodes, then we may distribute the power constraint unevenly. This can help with those nodes which are the most power-constrained (Baranidharan et al., 2014). If, for example, we have a star network then the nodes at the edge may be battery-powered or may be harvesting energy, whilst the central node could be mains powered. This is exactly what happens in a WSN light switch application. The edge nodes are the light switches. In some cases, these are power harvesting from the push action on the switch itself. Such nodes do not need to transmit regularly, only when operated.

However, simply reducing the transmit time is only one of the available possibilities for power saving. We could design the system to make the node idle most of the time rather than actively receiving. But better than this, is actually to switch the transceiver/node off when not in use, i.e., put the circuits into a sleep mode. To have nodes mostly sleeping is the aim of many power-constrained WSNs since, active or idle transceiver circuitry is the largest power drain within a node, including the sensors and the processor. The power consumption data in Figure 8.8 were gathered from measurements by Shurgers et al. (2001).

We have then sacrificed latency for power savings. This is because if a node sleeps, we must either wait for a node to wake up if it does so periodically, or we must cause it to wake up by some external action. We have also sacrificed network flexibility since the edge nodes are not fully functional routers and cannot be used to extend the network (Hamidzadeh and Ghomanjani, 2018).

This is directly related both to the choice of system design in 802.15.4 of end nodes versus coordinators (reduced functionality, and thus reduced power consumption) and to the choice of whether 802.15.4 uses regular beaconing or a random-access mode (which allows the nodes to sleep for longer) (Ali et al., 2015).



	Transmit	Receive	Idle	Off (Sleep)
Power consumed (mW)	14.88	12.5	12.35	0.016

Figure 8.8. Relative power consumption of different radio modes.

Source: https://www.cambridge.org/core/books/essentials-of-wireless-mesh-networking/0DE3EF74BA5FEE59999B18001B4293B0.

Finally, for balance, it must be said that not all WSNs have power consumption at the very top of their list of requirements. Emergency services use WSNs for vital signs monitoring of active staff and environment monitoring. Here battery life is important but equally important is network flexibility and low latency. Such WSNs are designed for low power but do not typically enter sleep modes. The personnel monitoring units need to be fully functional routers such that any node may extend the network, but they may have reduced processing power compared to the base unit (Pantelopoulos and Bourbakis, 2009).

REFERENCES

1. Abbasi, A. A., & Younis, M., (2007). A survey on clustering algorithms for wireless sensor networks. *Computer Communications*, *30*(14–15), 2826–2841.
2. Akyildiz, I. F., & Wang, X., (2005). A survey on wireless mesh networks. *IEEE Communications Magazine*, *43*(9), 523–530.
3. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E., (2002). Wireless sensor networks: A survey. *Computer Networks*, *38*(4), 393–422.
4. Akyildiz, I. F., Wang, X., & Wang, W., (2005). Wireless mesh networks: A survey. *Computer Networks*, *47*(4), 445–487.
5. Ali, S., Qaisar, S. B., Saeed, H., Khan, M. F., Naeem, M., & Anpalagan, A., (2015). Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring. *Sensors*, *15*(4), 7172–7205.
6. Baars, H., & Kemper, H. G., (2008). Management support with structured and unstructured data: An integrated business intelligence framework. *Information Systems Management*, *25*(2), 132–148.
7. Baranidharan, B., Srividhya, S., & Santhi, B., (2014). Energy efficient hierarchical unequal clustering in wireless sensor networks. *Indian Journal of Science and Technology*, *7*(3), 301.
8. Bartko, W. T., & Eccles, J. S., (2003). Adolescent participation in structured and unstructured activities: A person-oriented analysis. *Journal of Youth and Adolescence*, *32*(4), 233–241.
9. Bose, P., & Morin, P., (2004). Online routing in triangulations. *SIAM Journal on Computing*, *33*(4), 937–951.
10. Bose, P., Carmi, P., & Durocher, S., (2013). Bounding the locality of distributed routing algorithms. *Distributed Computing*, *26*(1), 39–58.
11. Boukerche, A., Cheng, X., & Linus, J., (2005). A performance evaluation of a novel energy-aware data-centric routing algorithm in wireless sensor networks. *Wireless Networks*, *11*(5), 619–635.
12. Callaghan, M. J., McBride, M., Harkin, J., & McGinnity, T. M., (2006). Internal location-based services using wireless sensor networks and RFID technology. *IJCSNS International Journal of Computer Science and Network Security*, *6*(4), 108–113.

13. Casilari, E., Cano-García, J. M., & Campos-Garrido, G., (2010). Modeling of current consumption in 802.15. 4/ZigBee sensor motes. *Sensors*, *10*(6), 5443–5468.
14. Castagnetti, A., Pegatoquet, A., Belleudy, C., & Auguin, M., (2012). A framework for modeling and simulating energy harvesting WSN nodes with efficient power management policies. *EURASIP Journal on Embedded Systems*, *2012*(1), 1–20.
15. Chowdhury, J., Reardon, J., & Srivastava, R., (1998). Alternative modes of measuring store image: An empirical assessment of structured versus unstructured measures. *Journal of Marketing Theory and Practice*, *6*(2), 72–86.
16. Chugh, A., & Panda, S., (2019). Energy efficient techniques in wireless sensor networks. *Recent Patents on Engineering*, *13*(1), 13–19.
17. Deebak, B. D., & Al-Turjman, F., (2020). A hybrid secure routing and monitoring mechanism in IoT-based wireless sensor networks. *Ad Hoc Networks*, *97*, 102022.
18. Denardin, G. W., Barriquello, C. H., Campos, A., & do Prado, R. N., (2011). A geographic routing hybrid approach for void resolution in wireless sensor networks. *Journal of Systems and Software*, *84*(10), 1577–1590.
19. Deutsch, D., (1980). The processing of structured and unstructured tonal sequences. *Perception & Psychophysics*, *28*(5), 381–389.
20. Ding, X., Tian, Y., & Yu, Y., (2015). A real-time big data gathering algorithm based on indoor wireless sensor networks for risk analysis of industrial operations. *IEEE Transactions on Industrial Informatics*, *12*(3), 1232–1242.
21. Dubey, A. K., (2019). An efficient variable distance measure k-means [VDMKM] algorithm for cluster head selection in WSN. *International Journal of Innovative Technology and Exploring Engineering*, *9*(1), 87–92.
22. El Alami, H., & Najid, A., (2019). ECH: An enhanced clustering hierarchy approach to maximize lifetime of wireless sensor networks. *IEEE Access*, *7*, 107142–107153.
23. Fang, C., Qian, L., Yao, G., & Liu, H., (2013). MR-MAC: A multiple reservation asynchronous MAC protocol for wireless sensor networks. *IEICE Transactions on Communications*, *96*(1), 317–320.

24. Ferrari, G., Medagliani, P., Di Piazza, S., & Martalo, M., (2007). Wireless sensor networks: Performance analysis in indoor scenarios. *EURASIP Journal on Wireless Communications and Networking*, *2007*, 1–14.

25. Fuentes-Fernández, R., Guijarro, M., & Pajares, G., (2009). A multi-agent system architecture for sensor networks. *Sensors*, *9*(12), 10244–10269.

26. García Villalba, L. J., Sandoval Orozco, A. L., Trivino Cabrera, A., & Barenco, A. C. J., (2009). Routing protocols in wireless sensor networks. *Sensors*, *9*(11), 8399–8421.

27. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M., (2013). Internet of things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, *29*(7), 1645–1660.

28. Hamidzadeh, J., & Ghomanjani, M. H., (2018). An unequal cluster-radius approach based on node density in clustering for wireless sensor networks. *Wireless Personal Communications*, *101*(3), 1619–1637.

29. Huang, H., Yin, H., Min, G., Zhang, J., Wu, Y., & Zhang, X., (2017). Energy-aware dual-path geographic routing to bypass routing holes in wireless sensor networks. *IEEE Transactions on Mobile Computing*, *17*(6), 1339–1352.

30. Hussian, R., Sharma, S., Sharma, V., & Sharma, S., (2013). WSN applications: Automated intelligent traffic control system using sensors. *Int. J. Soft Comput. Eng.*, *3*(3), 77–81.

31. Irandegani, M., & Bagherizadeh, M., (2017). Designing an asynchronous multi-channel media access control protocol based on service quality for wireless sensor networks. *International Journal of Advanced Computer Research*, *7*(32), 190.

32. Jourdan, Z., Rainer, R. K., & Marshall, T. E., (2008). Business intelligence: An analysis of the literature. *Information Systems Management*, *25*(2), 121–131.

33. Juels, A., (2006). RFID security and privacy: A research survey. *IEEE Journal on Selected Areas in Communications*, *24*(2), 381–394.

34. Kabara, J., & Calle, M., (2012). MAC protocols used by wireless sensor networks and a general method of performance evaluation. *International Journal of Distributed Sensor Networks*, *8*(1), 834784.

35. Karray, F., Jmal, M. W., Garcia-Ortiz, A., Abid, M., & Obeid, A. M., (2018). A comprehensive survey on wireless sensor node hardware platforms. *Computer Networks*, *144*, 89–110.
36. Karthikeyan, K., & Kavitha, M., (2013). Comparative analysis of data centric routing protocols for wireless sensor networks. *International Journal of Scientific and Research Publications*, *3*(1), 1–6.
37. Khan, M. N., Rahman, H. U., & Khan, M. Z., (2020). An energy efficient adaptive scheduling scheme (EASS) for mesh grid wireless sensor networks. *Journal of Parallel and Distributed Computing*, *146*, 139–157.
38. Khan, S., Parkinson, S., & Qin, Y., (2017). Fog computing security: A review of current applications and security solutions. *Journal of Cloud Computing*, *6*(1), 1–22.
39. Khandelwal, A., & Jain, Y. K., (2018). An efficient k-means algorithm for the cluster head selection based on SAW and WPM. *International Journal of Advanced Computer Research*, *8*(37), 191–202.
40. Krishnamachari, B., Estrin, D., & Wicker, S., (2002). *Modelling Data-Centric Routing in Wireless Sensor Networks, 2*, 39–44.
41. Kumar, V., Kumar, V., Sandeep, D. N., Yadav, S., Barik, R. K., Tripathi, R., & Tiwari, S., (2018). Multi-hop communication based optimal clustering in hexagon and Voronoi cell structured WSNs. *AEU-International Journal of Electronics and Communications*, *93*, 305–316.
42. Lee, J. W., Lee, J. Y., & Lee, J. J., (2012). Jenga-inspired optimization algorithm for energy-efficient coverage of unstructured WSNs. *IEEE Wireless Communications Letters*, *2*(1), 34–37.
43. Lee, J., (2017). Optimal power allocating for correlated data fusion in decentralized WSNs using algorithms based on swarm intelligence. *Wireless Networks*, *23*(5), 1655–1667.
44. Liu, M., Cao, J., Chen, G., & Wang, X., (2009). An energy-aware routing protocol in wireless sensor networks. *Sensors*, *9*(1), 445–462.
45. Mascarenas, D. L., Todd, M. D., Park, G., & Farrar, C. R., (2007). Development of an impedance-based wireless sensor node for structural health monitoring. *Smart Materials and Structures*, *16*(6), 2137.
46. Mishra, S., & Thakkar, H., (2012). Features of WSN and data aggregation techniques in WSN: A survey. *Int. J. Eng. Innov. Technol. (IJEIT)*, *1*(4), 264–273.

47. Muzakkari, B. A., Mohamed, M. A., Kadir, M. F., & Mamat, M., (2020). Queue and priority-aware adaptive duty cycle scheme for energy efficient wireless sensor networks. *IEEE Access*, *8*, 17231–17242.
48. Muzakkari, B. A., Mohamed, M. A., Kadir, M. F., Mohamad, Z., & Jamil, N., (2018). Recent advances in energy efficient-QoS aware MAC protocols for wireless sensor networks. *International Journal of Advanced Computer Research*, *8*(38), 212–228.
49. Nayyar, A., & Singh, R., (2019). IEEMARP-a novel energy efficient multipath routing protocol based on ant colony optimization (ACO) for dynamic sensor networks. *Multimedia Tools and Applications*, *4*(2), 1–32.
50. Ott, A., (2012). Wireless Networking with IEEE 802.15. 4 and 6 LoWPAN. In: *Embedded Linux Conference Europe* (Vol. 5, pp. 4–9).
51. Pantelopoulos, A., & Bourbakis, N. G., (2009). A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *40*(1), 1–12.
52. Petrioli, C., Nati, M., Casari, P., Zorzi, M., & Basagni, S., (2013). ALBA-R: Load-balancing geographic routing around connectivity holes in wireless sensor networks. *IEEE Transactions on Parallel and Distributed Systems*, *25*(3), 529–539.
53. Pughat, A., & Sharma, V., (2017). Performance analysis of an improved dynamic power management model in wireless sensor node. *Digital Communications and Networks*, *3*(1), 19–29.
54. Raja, L., Dhaka, V. S., & Poonia, R. C., (2015). The performance-based evaluation of models and routing protocols for Indian automotive networks. *Communications on Applied Electronics (CAE)*, *3*(1), 6–11.
55. Rani, S., Ahmed, S. H., Talwar, R., & Malhotra, J., (2017). Can sensors collect big data? An energy-efficient big data gathering algorithm for a WSN. *IEEE Transactions on Industrial Informatics*, *13*(4), 1961–1968.
56. Raptis, T. P., Passarella, A., & Conti, M., (2020). A survey on industrial Internet with ISA100 wireless. *IEEE Access*, *8*, 157177–157196.
57. Rawat, P., Singh, K. D., Chaouchi, H., & Bonnin, J. M., (2014). Wireless sensor networks: A survey on recent developments and potential synergies. *The Journal of Supercomputing*, *68*(1), 1–48.
58. Schurgers, C., & Srivastava, M. B., (2001). Energy efficient routing in wireless sensor networks. In: *2001 MILCOM Proceedings*

Communications for Network-Centric Operations: Creating the Information Force, 1, 357–361.

59. Shamsan Saleh, A. M., Ali, B. M., Rasid, M. F. A., & Ismail, A., (2014). A survey on energy awareness mechanisms in routing protocols for wireless sensor networks using optimization methods. *Transactions on Emerging Telecommunications Technologies*, *25*(12), 1184–1207.
60. Singh, S. K., Singh, M. P., & Singh, D. K., (2010). Energy-efficient homogeneous clustering algorithm for wireless sensor network. *International Journal of Wireless & Mobile Networks (IJWMN)*, *2*(3), 49–61.
61. Srbinovski, B., Magno, M., Edwards-Murphy, F., Pakrashi, V., & Popovici, E., (2016). An energy aware adaptive sampling algorithm for energy harvesting WSN with energy hungry sensors. *Sensors*, *16*(4), 448.
62. Stasser, G., Taylor, L. A., & Hanna, C., (1989). Information sampling in structured and unstructured discussions of three-and six-person groups. *Journal of Personality and Social Psychology*, *57*(1), 67.
63. Suryadevara, N. K., Mukhopadhyay, S. C., Kelly, S. D. T., & Gill, S. P. S., (2014). WSN-based smart sensors and actuator for power management in intelligent buildings. *IEEE/ASME Transactions on Mechatronics*, *20*(2), 564–571.
64. Waharte, S., Boutaba, R., Iraqi, Y., & Ishibashi, B., (2006). Routing protocols in wireless mesh networks: Challenges and design considerations. *Multimedia Tools and Applications*, *29*(3), 285–303.
65. Wang, S., Zhang, Z., Ye, Z., Wang, X., Lin, X., & Chen, S., (2013). Application of environmental internet of things on water quality management of urban scenic river. *International Journal of Sustainable Development & World Ecology*, *20*(3), 216–222.
66. Want, R., (2006). An introduction to RFID technology. *IEEE Pervasive Computing*, *5*(1), 25–33.
67. Weinstein, R., (2005). RFID: A technical overview and its application to the enterprise. *IT Professional*, *7*(3), 27–33.
68. Wethington, E., & McDarby, M. L., (2015). Interview methods (structured, semistructured, unstructured). *The Encyclopedia of Adulthood and Aging*, *3*, 1–5.

69. Ye, F., Zhong, G., Lu, S., & Zhang, L., (2005). Gradient broadcast: A robust data delivery protocol for large scale sensor networks. *Wireless Networks*, *11*(3), 285–298.
70. Zabin, F., Misra, S., Woungang, I., Rashvand, H. F., Ma, N. W., & Ali, M. A., (2008). REEP: Data-centric, energy-efficient, and reliable routing protocol for wireless sensor networks. *IET Communications*, *2*(8), 995–1008.
71. Zeb, A., Islam, A. M., Zareei, M., Al Mamoon, I., Mansoor, N., Baharun, S., & Komaki, S., (2016). Clustering analysis in wireless sensor networks: The ambit of performance metrics and schemes taxonomy. *International Journal of Distributed Sensor Networks*, *12*(7), 4979142.
72. Zhang, H., & Shen, H., (2009). Energy-efficient beaconless geographic routing in wireless sensor networks. *IEEE Transactions on Parallel and Distributed Systems*, *21*(6), 881–896.
73. Zhang, R., Pan, J., Xie, D., & Wang, F., (2015). NDCMC: A hybrid data collection approach for large-scale WSNs using mobile element and hierarchical clustering. *IEEE Internet of Things Journal*, *3*(4), 533–543.

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Wireless Mesh Networks

Wireless mesh networks (WMNs) will dominate in the coming decade as they are one of the primary technologies. They will assist in understanding the awaited dream of network connectivity anywhere, at any time, at a low cost. As a result, in the next-generation Internet, they will play a significant part. Their ability to self-organize greatly minimizes the complexity of network implementation and maintenance, necessitating a low initial investment. Simple mesh clients and mesh routers make up these networks, which make the backbone of WMNs. Mesh routers have limited mobility. They connect mesh and traditional clients to the network. The bridge functionalities and the gateway in mesh routers can be used to connect WMNs to other networks like the cellular, Internet, IEEE 802.16, IEEE 802.15, IEEE 802.11, sensor networks, etc. Mesh clients can be mobile or motionless, and they can establish a client mesh network with mesh routers and other mesh clients. Wireless personal area networks (WPANs), wireless metropolitan area networks (MAN), Ad hoc networks, and wireless local area networks (WLANs) are expected to benefit from WMNs, which are expected to overcome restrictions and considerably increase performance. These networks provide wireless services to various applications in metropolitan locations, local, campus, and personal. Wireless networks have advanced at a breakneck pace, inspiring a slew of new deployments. Around the world, research has increased, and numerous companies have already released products to the market, while others have begun to implement these networks in several application situations. Despite recent developments in wireless mesh networking, there are still several research difficulties to overcome. Worldwide, research is being carried out at a breakneck pace, with many articles already published in the literature, and the race to enhance this technology is continuing. The book goes through each mesh layer's functionality, as well as existing algorithms and protocols. Each chapter aims to show readers what is now accessible and how these networks might be enhanced and progressive by highlighting open research issues. The first chapter provides an overview of WMNs, such as essential design elements, characteristics, network architectures, and common application situations. In chapter 2, advanced physical methods for WMNs are covered, including adaptive coding and modulation, multi-radio systems, multi-channel systems, multiantenna systems, and software radios. In chapter 3, several medium access control (MAC) protocols for WMNs are presented and compared, ranging from multiple multi-channel MAC protocols, TDMA-based MAC, CDMA-based MAC, and carrier-sense multi-access with collision avoidance (CDMA/CA) variations. The routing protocols for WMNs are covered in Chapter 4. Different WMN routing metrics are examined and compared. Various types of routing protocols are also discussed. The fundamentals of numerous basic transport protocols are introduced in Chapter 5, followed by examining various transport protocols proposed for multi-hop wireless networks, including WMN. The security issues are discussed in Chapter 6. The security methods defined in IEEE 802.16 and 802.11 are offered first, afterward a thorough examination of security protocols for wireless mesh networks (WMNs) and ad hoc networks.
Different methods for managing and controlling WMNs are discussed in Chapter 7, including power management, topology management, network synchronization, and mobility management. The capacity analysis is the subject of Chapter 8. Diverse analytical methods for calculating wireless network capacity are discussed, as well as different capacity bounds. For WMNs, the existing capacity bounds are also reviewed, as well as their benefits and drawbacks.
We realized that this is the time to publish this book, which is aimed at teaching graduate students, motivating them for novel research ideas, and giving industry and academic experts with in-depth understanding and a detailed overview of the state-of-the-art in wireless mesh networking and representing how they can advance it, after working closely with engineers, researchers, and students. The book will fill a void in the literature by providing a complete overview of all study findings on this topic available in the last few years.

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