A Comprehensive Analysis on the Advancements, Architectures, and Challenges of Wireless Mesh Networks in Enhancing Modern Communication Technologies

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Abstract

This paper explores the advancements and significance of Wireless Mesh Networks (WMNs) in modern communication technologies, particularly their role in enhancing 4G, 5G, and beyond. It examines the architecture, types of nodes, and various standards of WMNs, highlighting their dynamic, self-organizing nature and cost-effectiveness. The paper also compares WMNs with ad-hoc networks, addressing protocol design and other critical issues. This paper provides a comprehensive analysis of the potential of WMNs to provide flexible, scalable, and reliable network solutions, and can serve as an essential reference for researchers and industry professionals.

Keywords: Wireless Mesh Networks, Multi-hop Communication, IEEE 802.11s Standard, Broadband Wireless Access, Self-organizing Networks.

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1. Introduction

Recent developments in Wireless Mesh Networks (WMNs) and internet technologies are not only playing a vital role in our daily life routines but also have contributed greatly towards the technologies such as 4G, 5G and beyond. WMN is a subset of wireless multiple-hop networks, and it is a combination of both conventional and mobile ad hoc networks. This technology is totally dynamic in nature because it has no fixed configuration, and therefore, routing protocol optimization becomes an important issue in WMNs.

WMNs are playing a substantial role in improving the performances of both traditional and mobile ad hoc networks. It provides flexibility, adaptive, and reconfigurable design while providing services at a very low cost to many service providers [1]. Unlike traditional Wi-Fi networks, where every access point must be connected via wired technology, Wireless Mesh Networks require only a few access points to have wired connections. Access points connected to wired networks are known as Internet Gateways (IGWs), while those without wired connections are called Mesh Routers (MRs). Mesh routers connect to internet gateways using multi-hop communication, and these gateways facilitate connections to external networks such as cellular, sensor, and internet networks.

A WMN consists of wireless devices arranged in for of a mesh, and devices could include Mesh Clients (MCs), mesh gateways, and mesh routers. These routers and clients are used to access internet resources, with routers generally connected to each other using a multi-hop architecture. This network is highly popular due to its mobility, flexibility, and ease of deployment for mobile devices. Each device or node in a wireless mesh environment has multiple paths for sending and receiving data. It can receive data from its neighbors and forward it to the next available device or node to reach its final destination, where each mobile node can function as both a mobile router and a host. In this setup, access points (APs) for other clients are mobile routers, and sometimes these routers can also serve as gateways to internet resources through fast wired connections. This innovative technology enables people living in isolated areas and small businesses operating in rural regions to access internet services. WMNs can be utilized for various public safety applications, such as in parking areas, schools, and universities.

The rest of this paper is organized as follows: Section 2 discusses the types of nodes in WMNs, including mesh routers and mesh clients. Section 3 examines the architecture of WMNs, detailing infrastructure mesh, client WMNs, and hybrid WMNs. Section 4 reviews the standards relevant to WMNs, with a focus on IEEE 802.11s. Section 5 outlines the key characteristics of WMNs, such as dynamic self-organizing capabilities and scalability. Section 6 compares WMNs with ad-hoc networks, highlighting differences in topology, mobility, and deployment. Section 7 addresses protocol design and other critical issues in WMNs, including challenges at various network layers. Finally, Section 8 explores the diverse applications of WMNs, ranging from broadband wireless access to healthcare and transportation systems.

2. Types of Nodes in WMNs

WMNs mostly consist of two types of radio nodes: Mesh Clients and Mesh Routers [2].

2.1. Mesh Routers

These are the backbone of the WMN, responsible for routing data between nodes within the network. They facilitate multi-hop communication and ensure data reaches its destination within the mesh. These nodes have more resources compared to mesh clients. Mesh routers possess greater processing power, battery capacity, and memory because they have additional responsibilities, such as performing data routing. To support these extra functionalities, they are equipped with multiple network interface cards (NICs) to handle various interfaces and functions. While mesh routers perform similar tasks to traditional wireless routers, they consume significantly less power by utilizing multi-hop communications.

2.2. Mesh Clients

MCs, in some cases, may also play the role of mesh routers, however, they are not capable acting as/replacing gateways or bridges of the wireless mesh networks. Also, mesh clients are fitted with a single

NIC as they only interact with one wireless mesh interface. These network devices generally have a simpler design compared to mesh routers and are available in a variety of electronic devices, such as laptops, PDAs, and desktop PCs.

3. WMNs Architecture

WMNs architecture falls into three categories essentially based on node functionality [3]. The categories are discussed below.

3.1. Infrastructure Mesh

In this type of architecture, MRs form an infrastructure for their attached MCs. In addition to IEEE 802.11 technologies, different types of radio technologies can be used to construct the infrastructure mesh. MRs are self-configuring, and multiple paths exist among these routers in the form of a mesh, providing connectivity to the internet through gateway functionality.

This method also provides backbone infrastructure for conventional clients, and the gateway/bridging functionality provided by mesh routers makes it possible to integrate Wireless Mesh Networks with existing wireless networks. Additionally, mesh clients can use an Ethernet interface to connect to mesh routers through Ethernet channels.

Conventional clients can communicate directly with MRs if they use similar radio technologies as the mesh routers. Otherwise, if conventional clients use different radio technologies, they will first communicate with base stations (BSs) that have Ethernet links to MRs.

This wireless mesh architecture is widely used, for example, in community and neighborhood networks. Normally, MRs are fixed on the rooftops of homes in a neighborhood, acting as access points. These APs provide access to internet resources for people in the area within the signal coverage. MRs support two kinds of radio: one for backbone communication through long-range communications and another for user communication.

3.2. Client WMNs

As the name suggests, this is a combination of both client and infrastructure models, incorporating the best qualities of both. In this model, clients can access the network via MRs or directly by using other MCs. The hybrid model provides links to other networks, such as the internet, Wi-Fi, WiMAX, sensor networks, and cellular networks, thus improving the coverage and connectivity capabilities of wireless mesh networks.

3.3. Hybrid WMNs

As the name hybrid suggests that this is the combination of both client and infrastructure models and good qualities of both are available in this model. In this model, not only clients can access the network by MRs but can also access directly by using other MCs. As hybrid model provides links to other networks e.g. it provides access to internet, Wi-Fi, WiMAX, sensor networks and cellular networks etc., thus, it improves the coverage and connectivity capabilities of wireless mesh networks.

4. WMNs Standards

A number of WMNs standards are available such as WPAN (Bluetooth, ZigBee), Wi-Fi (802.11a, b, g, n), WiMAX (802.16), IEEE 802.16a WMAN Mesh, and IEEE 802.11s WLAN Mesh etc. In favor of space, in this section, we will focus on only on IEEE 802.11s. This standard initially started in 2003, became a Task Group (TG) in July 2004, and the first draft was accepted in March 2006. Mainly, this standard concerns network architecture, internetworking, routing, security, and MAC enhancements. IEEE 802.11s uses Mesh Points (MPs), Mesh Access Points (MAPs), and Mesh Portal Points (MPPs) types of stations [4].

MPs are wireless stations that perform the routing function of the network. Mesh Access Points (MAPs) are similar to MPs but have additional functions. In addition to routing, MAPs aggregate traffic from/toward legacy 802.11 stations. Finally, Mesh Portal Points (MPPs) are Mesh Points that act as gateways to other external networks, such as the internet. The main role of MPPs is to aggregate traffic or data from/toward other external networks. Figure 2 illustrates the scenario discussed above.

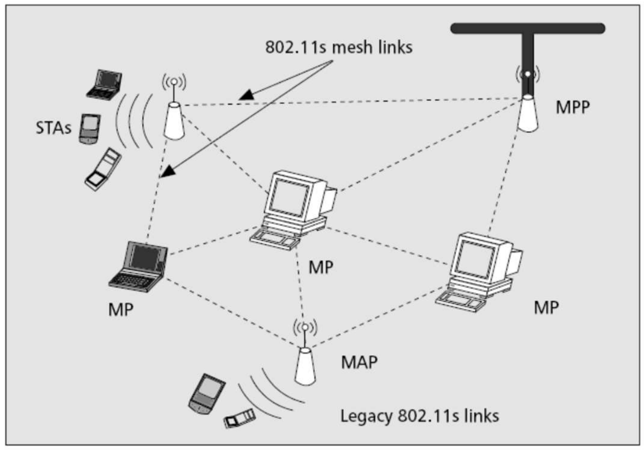

Figure 1: Wireless Mesh Network IEEE 802.11s

5. WMNs Characteristics

WMNs have several notable characteristics, some are outlined below [5].

5.1. Dynamic Self Organizing and Self Configuring

Ad hoc networking has enhanced the performance of wireless mesh networks by providing flexible network designs, easy deployment, simple configuration, and improved connectivity.

5.2. Low cost

It has reduced deployment costs. MRs are wireless and support multi-hop communication for information exchange over large areas. Therefore, these routers are less expensive compared to single hop wired routers.

5.3. Extremely adaptable and expendable

To increase network coverage, it is easy to add more network nodes. This addition of nodes can also help in areas where network configuration is difficult or blocked.

5.4. Increased Reliability

WMNs increase network reliability by providing multiple paths for data to travel to its destination or alternative paths in case of link failure. The availability of multiple paths in WMNs eliminates network congestion and distributes network loads across different links. This can significantly improve network reliability and throughput in wireless mesh networks.

5.5. Scalability

Compared to other wireless networks, where increasing the number of devices or nodes can negatively affect network performance, adding nodes in a WMN does not degrade performance. Instead, it enhances network performance by increasing transmission capacity, which helps with load balancing and provides alternative paths for data in case of node or link failure.

5.6. Interoperability

Hybrid multi-point to multi-point in WMNs makes them compatible with various available technologies, such as Cellular, Wi-Fi, Bluetooth, Wi-MAX, Sensor Networks, and Mobile Ad hoc Networks. All these networks are or will be capable of configuring a wireless mesh network and freely communicating with each other.

5.7. Fault tolerance and robustness

These networks offer fault tolerance and robustness due to the availability of multiple paths for data to travel from one device to another.

6. Comparison of Ad-hoc and Wireless Mesh Networks

There are a number of differences between Ad-hoc and Wireless Mesh Networks, however, the main differences are network topology and node mobility [6]. In this section, we discuss some key difference.

6.1. Network Topology

Wireless mesh networks have comparatively static network topologies, while ad-hoc networks are infrastructure-less and support highly dynamic topologies. This allows ad-hoc networks to adapt quickly to changes in the network environment.

6.2. Relay Node Mobility

Wireless mesh networks have comparatively static network topologies, while ad-hoc networks are infrastructure-less and support highly dynamic topologies. This allows ad-hoc networks to adapt quickly to changes in the network environment.

6.3. Deployment

Node deployment in ad-hoc networks is simple and easy, whereas in WMNs, it requires strategic planning. This planning ensures optimal performance and coverage in WMNs.

6.4. Infrastructure requirements

Wireless mesh networks have partial or fully fixed infrastructure, while ad-hoc networks are entirely infrastructure-less. This fixed infrastructure in WMNs provides stable and reliable communication paths.

6.5. Energy Constraints

Devices in WMNs have fewer energy constraints compared to ad-hoc network devices, which face higher energy constraints. This is because WMN devices are often connected to stable power sources.

7. Protocol Design and Other Issues in WMNs

7.1. Protocol design Issues

Designing a protocol to work for a WMN is critical as it requires more effort compared to other areas of the network. Therefore, it is important for protocol designers to fully understand the network architecture, network topology, traffic patterns, network node density, number of channels used for each node, transmission power levels, and node mobility factors, as well as the connections among these factors, to design an efficient protocol for WMNs. The following are some protocol design issues at different layers [5].

7.1.1. Physical layer issues

The radios of wireless mesh networks support several transmission speeds, modulation types, and coding techniques. The WMN challenges for physical layer are almost the same as for other wireless technologies, however, WMN physical layer is relatively reliable in the context of its performance. The adverse effects of fading and interference need to be carefully considered, and solutions such as Orthogonal Frequency Division Multiplexing (OFDM), Ultra-Wideband (UWB), Frequency Hopping Spread Spectrum (FHSS), and Code Division Multiple Access (CDMA) are being utilized to increase the reliability of WMNs. Besides these techniques, other methods can also be used to improve the performance of wireless mesh networks, such as node mobility, variable transmission power, multiple transceivers, and directional antennas.

7.1.2. MAC layer issues

Due to its support for multi-hop communication, MAC layer of WMNs is difference from other wireless networks. Protocols for this layer need to be designed to operate on single or multiple channels simultaneously. Other MAC layer challenges for WMNs include their distributed nature and self-organization; they need to be collaborative for better coordination among neighboring nodes as well as nodes at multiple hop distances. To increase the reliability and capacity of WMNs, multiple input and multiple output (MIMO) wireless radios have been anticipated. Although WMN mobility is considerably low, it still affects MAC performance and prevents the network from fully benefiting from many WMN improvements.

7.1.3. Transport layer issues

Many transport layer protocols exist for both WMNs and other wireless ad hoc networks, but there is still no efficient transport protocol specifically for WMNs. The unique characteristics of WMNs, such as multi-hop communication and dynamic topology, pose significant challenges for transport layer protocol design. Additionally, issues like varying link quality and interference further complicate the development of a robust and efficient transport protocol for WMNs.

7.1.4. Network layer issues

Although many network layer or routing protocols exist for ad hoc networks, a lot of work still needs to be done for WMNs to find the best routing protocol. Scalability, multiple performance metrics, efficient routing with mesh infrastructure, and robustness factors must be considered for optimal routing protocols for WMNs. Additionally, protocols must handle the dynamic nature of WMNs and ensure reliable data transmission across multiple hops.

7.1.5. Application Layer

A number of different applications can be performed by WMNs, typically divided into categories such as internet access, sharing information across multiple wireless networks, and distributed information storage and sharing. To design new and efficient application layer protocols for WMNs, these categories must be considered.

7.2. Other Issues in WMNs

Apart from the above issues at the different layers, there are several others critical issues that could degrade a WMN's performance [7].

7.2.1. Radio techniques

Over the past few years, many network devices such as directional and smart antennas, MIMO, and multi-radio systems have been developed to increase network performance. For further enhancements, advanced radio techniques are used for wireless networks, such as reconfigurable, software radio, and frequency agile/cognitive radios. This radio technology is still new and requires improvement in higher layer protocols, particularly in MAC layer and routing protocols. This technology might be the future platform for wireless communications due to its dynamic control capability.

7.2.2. Scalability

Scalability is also an important issue in wireless mesh networks (WMNs). Without scalability, network performance is notably reduced when more devices are added to the network. Many communication or routing protocols suffer from network scalability issues, making it difficult for routing protocols to find reliable links for data packets. Transport layer protocols might lose connections, and MAC layer protocols could cause throughput reduction. Ensuring scalability is crucial for maintaining efficient network operations as the network grows.

7.2.3. Mesh connectivity

WMNs benefit greatly from mesh connections among different network devices. For successful mesh connectivity, network self-organization and topology algorithms are required. These algorithms help maintain robust and efficient communication paths within the network. Additionally, ensuring seamless integration and coordination among nodes is essential for optimal mesh connectivity.

7.2.4. Broadband and QoS

Applications of WMNs include broadband services with varied requirements, such as end-to-end transmission delay, fairness, per device/node throughput, and data loss proportion. These metrics need to be measured and optimized to ensure high-quality service. Furthermore, maintaining consistent QoS across different applications and user demands is critical for the overall performance of WMNs.

7.2.5. Compatibility and inter-operability

Compatibility and interoperability are crucial prerequisites for wireless mesh networks to maintain access not only for mesh clients but also for conventional clients. This network needs to be backward compatible with conventional clients; otherwise, the interest in wireless mesh networks would be considerably compromised. Ensuring seamless integration with existing technologies and standards is essential for widespread adoption and functionality.

7.2.6. Security

Security is a significant issue in WMNs, just as it is in other networks. Recently, many security techniques have been used for wireless LANs, but these techniques are not fully applicable to wireless mesh networks. For example, WMNs rely on a distributed system design and lack a central command or centralized trusted authority to distribute public keys for secure communication between nodes [8]. Many security techniques used for ad hoc networks could be applied to WMNs, but these techniques are still new and may not be practically implementable in WMNs.

7.2.7. Ease of use

Protocols need to be designed to meet certain requirements of WMNs, such as self-organization, power management, performance monitoring, dynamic topology control, efficient network operation maintenance, robustness to link failures, and fast subscription/user authentication methods. Ensuring these protocols are user-friendly and easy to implement is crucial for the widespread adoption of WMNs.

8. Applications

Today, various companies have recognized the importance of WMNs and have started manufacturing their own mesh networking devices or protocols for a wide range of applications. Many of these devices are based on IEEE 802.11 hardware, and most companies are trying to implement their own devices or routing protocols for network configuration and routing purposes. As a result, integrating mesh devices or protocols from different companies into a single WMN is not an easy task. The following are some applications of WMNs [9].

8.1. Broadband wireless access

Broadband can play an extremely important role in boosting a country’s economy due to its wide range of applications, such as video conferencing, online information sharing, online gaming, video on demand, and telecommunications. These latest applications have a significant impact on our daily lives. For example, telecommunications can reduce daily travel, increase time savings, and decrease road congestion. In this way, broadband technology offers many benefits to our lives.

Wireless mesh networks (WMNs) can be easily created using inexpensive devices, allowing service providers to quickly realize the advantages and savings. Due to the low operational costs of WMNs, it is possible for people to access free broadband.

8.2. Industrial applications

Wired networks are expensive for building monitoring and device control, such as air conditioners, lights, and elevators. These networks are costly in terms of deployment complexity and maintenance. While Wi-Fi offers a solution and reduces costs slightly, it does not meet the required performance levels satisfactorily. Therefore, the best solution for industrial applications is the deployment of mesh routers, which are simpler and more cost-effective.

8.3. Healthcare

WMNs can be implemented in hospitals and medical centers for various valuable operations, such as sharing patient medical histories, test results, and insurance information. Many hospitals currently use broadband technology for data sharing, like medical images. However, this technology is somewhat expensive. Instead, WMNs should be considered as they are cheaper and can be easily deployed.

8.4. Transportation System

IEEE 802.11 and IEEE 802.16 networks are not feasible solutions for transportation systems due to their limited access. To extend internet access to public buses, airplanes, trains, and ferries, WMN technology is the best option. With WMN technology, passengers can easily use internet resources while traveling. Additionally, drivers can communicate with each other, remotely monitor their vehicles, and manage security cameras.

8.5. Hospitality

WMNs are highly utilized by hotels and resorts for fast and free internet connectivity. They are cheap, easy to build, and flexible for network structure changes. This technology also enhances guest satisfaction by providing reliable and seamless internet access throughout the premises.

8.6. Warehouses

Handheld scanners used to maintain catalogs need connectivity throughout the entire warehouse. WMNs are cheap and easy to set up, making them ideal for modern warehouses and shipping logistics. They also support real-time inventory management, improving operational efficiency.

8.7. Pop-up Locations

Construction sites, architects, and engineers can benefit from WMNs. For example, they can use cameras to share information and communicate on-site, providing real-time project updates. Pop-up locations like street fairs, political rallies, and outdoor concerts can also utilize the low-cost and efficient WMNs.

9. Conclusion

This paper provides a comprehensive analysis of Wireless Mesh Networks, highlighting their architecture, types of nodes, and various standards. It discusses the dynamic, self-organizing nature of WMNs, their cost-effectiveness, and their scalability. By comparing WMNs with ad-hoc networks and addressing protocol design issues, the paper underscores the critical challenges and potential solutions in this field. Key highlights include the examination of multi-hop communication, fault tolerance, and interoperability with other networks. This work is significant as it offers valuable insights into the potential of WMNs to enhance modern communication technologies, making it a crucial resource for researchers and industry professionals aiming to develop flexible, scalable, and reliable network solutions.

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