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Wireless Mesh Networks: A Survey and Challenges Ahead

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***Abstract*— With the advances in wireless technologies and the explosive growth of the Internet, wireless networks, especially Wireless Mesh Networks (WMNs), are emerging towards a significant evolution. Wireless mesh networks have emerged as a key technology for next-generation wireless networking. Because of their advantages over other wireless networks, WMNs are undergoing rapid progress and inspiring numerous applications. Over the last few years, a plethora of studies has been carried out to improve the efficiency of wireless networks. In this paper, a survey of different aspects regarding WMNs design, current state-of-the-art protocols and algorithms for WMNs that have been proposed to improve their performance.**

***Index Terms*— Wireless Mesh Networks, WMN, Wireless, Topology Control, Routing, Self-organizing**

I. INTRODUCTION

With the proliferation of Internet, WMNs have become a practical wireless solution for providing community broadband Internet access services. WMNs are dynamically self-organized and self-configured, with the nodes in the network automatically establishing an ad hoc network and maintaining the mesh connectivity. WMNs are comprised of two types of nodes: mesh routers and mesh clients. These networks exhibit characteristics that are novel in the wireless context, and in many ways more similar to traditional wired networks [1]. In Infrastructure WMNs, Access Points (APs) provide internet access to Mesh Clients (MCs) by forwarding aggregated traffic to Mesh Routers (MRs), known as relays, in a multi-hop fashion until a Mesh Gateway (MG) is reached. MGs act as bridges between the wireless infrastructure and the Internet. Fig. 1 illustrates a typical WMN infrastructure. In such networks, each infrastructure node consists of multiple radios, and each radio is capable of accessing multiple orthogonal channels, referred as Multi-Radio Multi-Channel transmissions. Other than the routing capability for gateway/bridge functions as in a conventional wireless router, a mesh router contains additional routing functions to support mesh networking. Through multi-hop communications, the same coverage can be achieved by a mesh router with much lower transmission power. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies.
Fig.2 depicts the case of multiple radios routers where each router is equipped with two radio interfaces for the backhaul side communications and one radio interface for the client side communications; in a Multi-Radio Multi-channel network, simultaneous communications are possible by using non-interfering channels, which have the potential of significantly increasing the network capacity [2], [3], [4], [5].

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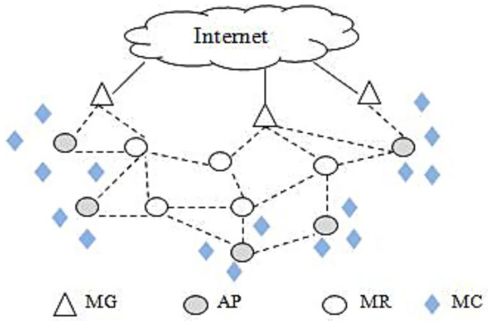

Fig. 1. Wireless mesh network infrastructure

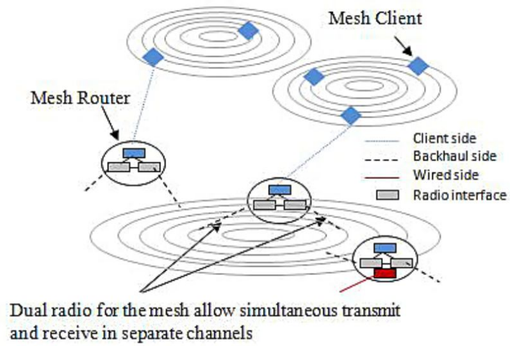

Fig. 2. Multi-radio Mesh Routers.

WMNs can provide large coverage area, lower costs of backhaul connections, prolong end-user battery life, and more importantly provide no LOS (Line Of Sight) connectivity among users without direct LOS links. However, several challenges remain so that a WMN performance in terms of throughput and delays match the performance of a wired network. Furthermore, earlier deployments of WMNs have been linked to a number of problems mainly related to connectivity problems (such as lack of coverage, dead spots or obstructions) and performance problems (low throughput and/or high latency) [6].
In this article, I present a survey of recent advances in protocols and algorithms for WMNs. The aim is to provide a better understanding of research challenges of this emerging technology. The rest of this article is organized as follows. Section II is devoted to the network architectures of WMNs, with an objective to highlight the characteristics of WMNs and the critical factors influencing protocol design. Section III provides a detailed study on recent advances of WMNs is then carried out, with an emphasis on open research issues.

II. Network Architecture And Critical Design Factors

A. Network Architecture

Infrastructure/Backbone WMNs
In this architecture, mesh routers form an infrastructure for clients, as shown in Fig. 3, where dashed and solid lines indicate wireless and wired links, respectively. The WMN infrastructure/backbone can be built using various types of radio technologies, in addition to the mostly used IEEE 802.11 technologies. The mesh routers form a mesh of self-configuring, self-healing links among themselves. With gateway functionality, mesh routers can be connected to the Internet. This approach, also referred to as infrastructure meshing, provides a backbone for conventional clients and enables integration of WMNs with existing wireless networks, through gateway/bridge functionalities in mesh routers.

Client WMNs
Client meshing provides peer-to-peer networks among client devices. Client nodes constitute the actual network to perform routing and configuration functionalities as well as providing end-user applications to customers. Hence, a mesh router is not required for these types of networks. Client WMNs are usually formed using one type of radios on devices Thus, a Client WMN is actually the same as a conventional ad hoc network, with additional requirement on end-user devices to perform additional functions such as routing and self-configuration.

Hybrid WMNs
This architecture is the combination of infrastructure and client meshing, as shown in Fig. 4. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks, the routing capabilities of clients provide improved connectivity and coverage inside WMNs.

B. Critical Design Factors

The critical factors influencing the performance of WMNs are summarized as follows.

Radio Techniques
Many approaches have been proposed to increase capacity and flexibility of wireless systems in recent years. Typical examples include directional and smart antennas, multiple input multiple output (MIMO) systems, and multi-radio/multi-channel systems. To further improve the performance of a wireless radio and control by higher layer protocols, more advanced radio technologies, such as reconfigurable radios, frequency agile/cognitive radios, and even software radios, have been used for wireless communication. These advanced wireless radio technologies all require a revolutionary design in higher-layer protocols, especially MAC and routing protocols.

Scalability
Scalability is a critical requirement of WMNs. Without support of this feature, the network performance degrades significantly as the network size increases.

Mesh Connectivity
Many advantages of WMNs originate from mesh connectivity. To ensure reliable mesh connectivity, network self-organization and topology control algorithms are needed

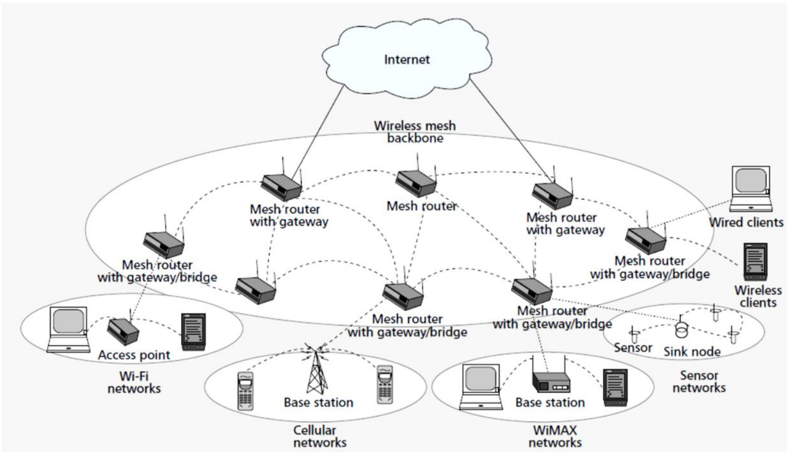

Fig. 3: Infrastructure/backbone WMNs.

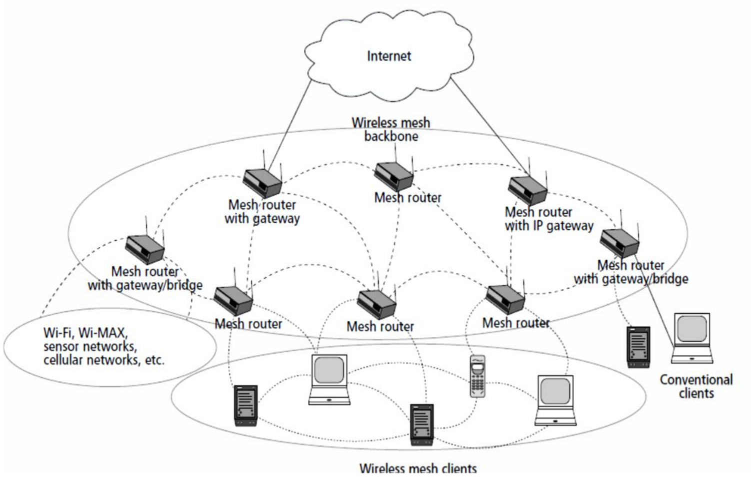

Fig. 4: Hybrid WMNs.

Broadband and QoS
Different from classical ad hoc networks, most applications of WMNs are broadband services with heterogeneous QoS requirements. Thus, in addition to end-to-end transmission delay and fairness, more

performance metrics, such as delay jitter, aggregate and per-node throughput, and packet loss ratios, must be considered by communication protocols.

Security
Although many security schemes have been proposed for wireless LANs in recent years, they are still not fully applicable for WMNs. For instance, there is no centralized trusted authority to distribute a public key in a WMN due to the distributed system architecture. The existing security schemes proposed for ad hoc networks can be adopted for WMNs. However, most of the security solutions for ad hoc networks are still not mature enough to be implemented practically.
Compatibility and Inter-operability. In WMNs it is a default requirement to support network access for both conventional and mesh clients. Therefore, WMNs need to be backward compatible with conventional client nodes.

III. ADVANCES AND RESEARCH CHALLENGES

Despite recent advances in the research and development in WMNs, many challenging problems still remain: the theoretical network capacity is still unknown, protocols in various layers need to be improved, new schemes are required for network management, and the network still lacks security.

A. Network Capacity

To date, much research has been carried out to study the capacity of ad hoc networks. Considering the similarities between WMNs and ad hoc networks, the results from that research can be adopted to study the capacity of WMNs.
Lower and upper bounds for ad hoc network capacity are derived in [7], where an important implication is pointed out as the guideline to improve the capacity of ad hoc networks: a node should only communicate with nearby nodes. To implement this idea, two major schemes are suggested in [7]:

- Throughput capacity can be increased by deploying relaying nodes.
- Nodes need to be grouped into clusters.

In other words, communication of a node with another node that is not nearby must be conducted via relaying nodes or clusters. However, considering a distributed system such as ad hoc networks or WMNs, clustering nodes or allocating relaying nodes is a challenging task. The scheme proposed in [8] increases network capacity of ad hoc networks by utilizing the node mobility. A source node will not send its packets until the destination node gets closer to it. Thus, via the node mobility, a node communicates only with its nearby nodes. This scheme has a limitation: the transmission delay is rather large and the required buffer for a node may become infinite.

B. Layered Communication Protocols

- *Physical Layer*

Wireless radios of existing WMNs are able to support multiple transmission rates by a combination of different modulation and coding rates. With such modes, adaptive error resilience can be provided through link adaptation. Schemes such as orthogonal frequency multiple access (OFDM) and ultra-wide band (UWB) techniques are being used to support high-speed transmissions. In order to further increase capacity and mitigate the impairment by fading, delay-spread, and co-channel interference, multi-antenna systems such as antenna diversity, smart antenna, and MIMO systems, have been proposed for wireless communications. Although these physical-layer techniques are also desired by other wireless networks, it is a more challenging problem to develop such techniques for WMNs.

- *MAC Layer*

There exist differences between the MAC in WMNs and the classical counterparts for wireless networks:

- MAC for WMNs is concerned with more than one-hop communication.
- MAC is distributed, needs to be collaborative, and works for multipoint-to-multipoint communication.
- Mobility is low but still affects the performance of MAC.

A MAC protocol for WMNs can be designed to work on a single channel or multiple channels simultaneously.

Single-Channel MAC
Three approaches are usually employed to design a single-channel MAC protocol for WMNs.

Modifying Existing MAC Protocols
In an IEEE 802.11 mesh network, the MAC protocol can be improved by adjusting parameters of CSMA/CA. But, such a solution can only achieve a low end-to-end throughput, because it cannot significantly reduce the probability of contentions among neighboring nodes.

Cross-Layer Design
Two major schemes exist in this category: directional antenna-based MACs and MACs with power control. The first set eliminates exposed nodes if the antenna beam is assumed to be perfect. However, due to the directional transmission, more hidden nodes are produced. The second set reduces exposed nodes, especially in a dense network, using low transmission power, and thus improve the spectrum spatial reuse factor in WMNs. However, the issue of hidden nodes may become worse because a lower transmission power level reduces the possibility of detecting a potential interfering node.

Multi-Channel MAC
To further improve network performance and also increase network capacity for WMNs, a favorable solution is to enable a network node to work on multiple channels instead of only on a single fixed channel.

- *Routing Layer*

Despite the availability of many routing protocols for ad hoc networks, the design of routing protocols for WMNs is still an active research area. An optimal routing protocol for WMNs must capture the following features:

- *Multiple Performance Metrics*. Many existing routing protocols use minimum hop-count as a performance metric to select the routing path. This has been demonstrated to be ineffective in many situations.
- *Scalability*. Setting up or maintaining a routing path in a very large wireless network may take a long time. Thus, it is critical to have a scalable routing protocol in WMNs.
- *Robustness*. To avoid service disruption, WMNs must be robust to link failures or congestion. Routing protocols also need to perform load balancing.
- *Efficient Routing with Mesh Infrastructure*. Considering the minimal mobility and no constraints on power consumption in mesh routers, the routing protocol in mesh routers is expected to be much simpler than ad hoc network routing protocols.

The impact of performance metrics on a routing protocol is studied in [9] where link quality source routing (LQSR) selects a routing path according to link quality metrics. Three performance metrics, i.e., expected transmission count (ETX), per-hop RTT, and per-hop packet pair, are implemented separately. The performance of the routing protocol with these three performance metrics is compared with the method using the minimum hop-count. For stationary nodes in WMNs, ETX achieves the best performance, while the minimum hop count method outperforms the three link quality metrics when nodes are mobile. This result illustrates that the link quality metrics used in [9] are still not enough for WMNs when mobility is concerned.
A multi-radio LQSR (MR-LQSR) is proposed in [10], where a new performance metric, called weighted cumulative expected transmission time (WCETT), is incorporated. WCETT takes into account both link quality metric and the minimum hop-count and achieves good tradeoff between delay and throughput. MR-LQSR assumes that all radios on each node are tuned to non-interfering channels with the assignment changing infrequently.
Multi-Path Routing are designed to perform better load balancing and to provide high fault tolerance. Multiple paths are selected between source and destination. When a link is broken on a path due to a bad channel quality or mobility, another path in the set of existing paths can be chosen. Thus, without waiting to set up a new routing path, the end-to-end delay, throughput, and fault tolerance can be improved. However, given a performance metric, the improvement depends on the availability of node disjoint routes between source and destination. Another drawback of multi-path routing is its complexity.

- *Security*

Similar to mobile ad hoc networks, WMNs still lack efficient and scalable security solutions, because their security is more easily compromised due to several factors: their distributed network architecture, the vulnerability of channels and nodes in the shared wireless medium, and the dynamic change of network topology. Attacks in different protocol layers can easily cause the network to fail. Attacks may occur in the routing protocol such as advertising wrong routing updates. It is possible for the attacker to sneak into the network, impersonate a legitimate node, and deviate the required specifications of a routing protocol. Similar types of attacks identified in routing protocols may also occur in MAC protocols. Attackers may also sneak into the network by misusing the cryptographic primitives. A widely accepted counter-attack measure is authentication and authorization. For wireless LANs, this is taken care of by authentication, authorization, and accounting (AAA) services directly over the access point or via gateways.

Additionally, security key management in WMNs is much more difficult than in wireless LANs, because of the lack of central authority, trusted third party, or server to manage security keys. Key management in WMNs needs to be performed in a distributed but secure manner. Therefore, a distributed authentication and authorization scheme with secure key management needs to be proposed for WMNs.

To further ensure security of WMNs, two more strategies need to be considered: embedding security mechanisms into network protocols such as secure routing and MAC protocols, or developing security monitoring and response systems to detect attacks, monitor service disruption, and respond quickly to attacks. For a secure networking protocol, a multi-protocol layer security scheme is desired, because security attacks occur simultaneously in different protocol layers. For a security monitoring system, a cross-layer framework also needs to be developed. Designing and implementing a practical security system, including cross-layer secure network protocols and various intrusion detection algorithms, is a challenging area of research.

- *Cross-Layer Design*

The methodology of layered protocol design does not necessarily lead to an optimum solution. This is particularly the case in WMNs. The physical channel in WMNs is variable in terms of capacity, bit error rate, etc. Although different coding, modulation, and error control schemes can be used to improve the performance of the physical channel, there is no way to guarantee fixed capacity, zero packet loss rate, or reliable connectivity. In order to provide satisfactory network performance, MAC, routing, and transport layer protocols need to interactively work together with the physical layer. In WMNs, because of their ad hoc feature, network topology constantly changes due to mobility and link failures. Such a dynamic network topology impacts multiple protocol layers. Thus, in order to improve protocol efficiency, cross-layer design become indispensable.

Cross-layer design can be performed in two ways. The first approach is to improve the performance of a protocol layer by taking into account parameters in other protocol layers. Typically, parameters in the lower protocol layers are reported to higher layers. For example, the packet loss rate in the MAC layer can be reported to the transport layer so that a TCP protocol is able to differentiate congestion from packet loss.. The second approach of cross-layer design is to merge several protocols into one component. For example, in ad hoc networks, MAC and routing protocols can be combined into one protocol in order to closely consider their interactions. The first approach keeps the transparency between protocol layers, while the second approach can achieve much better performance through closer interaction between protocols. Certain issues must be considered when carrying out cross layer protocol design: cross-layer designs have risks due to the loss of protocol-layer abstraction, incompatibility with existing protocols, unforeseen impact on the future design of the network, and difficulty in maintenance and management..

IV. CONCLUSION

Although WMNs can be built up based on existing technologies, field trials and experiments with existing WMNs prove that the performance of WMNs is still far below expectations. As explained throughout this article, there still remain many research problems. Among them, the most important and urgent ones are the scalability and the security.

Based on existing MAC, routing and transport protocols, network performance is not scalable with either the number of nodes or the number of hops in the network. This problem can be alleviated by increasing the network capacity through using multiple channels/radios per node or developing wireless radios with higher transmission speed. However, these approaches do not truly enhance the scalability of WMNs, because resource utilization is not actually improved. Therefore, in order to achieve scalability, it is essential to develop new MAC, routing, and transport protocols for WMNs.

WMNs are vulnerable to security attacks in various protocol layers. Current security approaches may be effective to a particular attack in a specific protocol layer. However, there still exists a need for a comprehensive mechanism to prevent or counter attacks in all protocol layers. Moreover, self-organization and self-configuration capability is a desired feature in WMNs. It requires protocols in WMNs to be distributive and collaborative. However, current WMNs can only partially realize this objective. Furthermore, current WMNs still have very limited capabilities of integrating heterogeneous wireless networks, due to the difficulty in building multiple wireless interfaces and the corresponding gateway/bridge functions in the same mesh router.

In spite of these open research problems, i believe that WMNs will be one of the most promising technologies for next-generation wireless networking.

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