A Survey on Wireless Mesh Networks

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Abstract

Wireless mesh networks (WMNs) 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. However, many technical issues still exist in this field. In order to provide a better understanding of the research challenges of WMNs, this article presents a detailed investigation of current state-of-the-art protocols and algorithms for WMNs. Open research issues in all protocol layers are also discussed, with an objective to spark new research interests in this field.

Introduction

Wireless mesh networks (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. 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. In spite of all these differences, mesh and conventional wireless routers are usually built based on a similar hardware platform.

Mesh routers have minimal mobility and form the mesh backbone for mesh clients. Thus, although mesh clients can also work as a router for mesh networking, the hardware platform and software for them can be much simpler than those for mesh routers. For example, communication protocols for mesh clients can be light-weight, gateway or bridge functions do not exist in mesh clients, only a single wireless interface is needed in a mesh client, and so on.

In addition to mesh networking among mesh routers and mesh clients, the gateway/bridge functionalities in mesh routers enable the integration of WMNs with various other networks. Conventional nodes equipped with wireless network interface cards (NICs) can connect directly to WMNs through wireless mesh routers. Customers without wireless NICs can access WMNs by connecting to wireless mesh routers through, for example, Ethernet. Thus, WMNs will greatly help users to be always-on-line anywhere, anytime.

Consequently, instead of being another type of ad-hoc networking, WMNs diversify the capabilities of ad-hoc networks. This feature brings many advantages to WMNs, such as low up-front cost, easy network maintenance, robustness, reliable service coverage, etc. Therefore, in addition to being widely accepted in the traditional application sectors of ad hoc networks, WMNs are undergoing rapid commercialization in many other application scenarios such as broadband home networking, community networking, building automation, high-speed metropolitan area networks, and enterprise networking.

To date, several companies have already realized the potential of this technology and offer wireless mesh networking products. A few testbeds have been established in university research labs. However, for a WMN to be all it can be, considerable research efforts are still needed. For example, the available MAC and routing protocols are not scalable; throughput drops significantly as the number of nodes or hops in WMNs increases. Thus, existing protocols need to be enhanced or re-invented for WMNs. Researchers have started to revisit the protocol design of existing wireless networks, especially of IEEE 802.11 networks, ad hoc networks, and wireless sensor networks, from the perspective of wireless mesh networking. Industrial standards groups, such as IEEE 802.11, IEEE 802.15, and IEEE 802.16, are all actively working on new specifications for WMNs.

In this article we present a survey of recent advances in protocols and algorithms for WMNs. Our aim is to provide a better understanding of research challenges of this emerging technology. The rest of this article is organized as follows. The network architectures of WMNs are first presented, with an objective to highlight the characteristics of WMNs and the critical factors influencing protocol design. A detailed study on recent advances of WMNs is then carried out, with an emphasis on open research issues. The article concludes with final remarks.

Network Architecture and Critical Design Factors

Network Architecture

The architecture of WMNs can be classified into three types:

Infrastructure/Backbone WMNs. In this architecture, mesh routers form an infrastructure for clients, as shown in Fig. 1, 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. Conventional clients with an Ethernet interface can be connected to mesh routers via Ethernet links. For conventional clients with the same radio technologies as mesh routers, they can directly communicate with mesh routers. If different radio technologies are used, clients must communicate with their base stations that have Ethernet connections to mesh routers.

Client WMNs. *Client meshing* provides peer-to-peer networks among client devices. In this type of architecture, 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

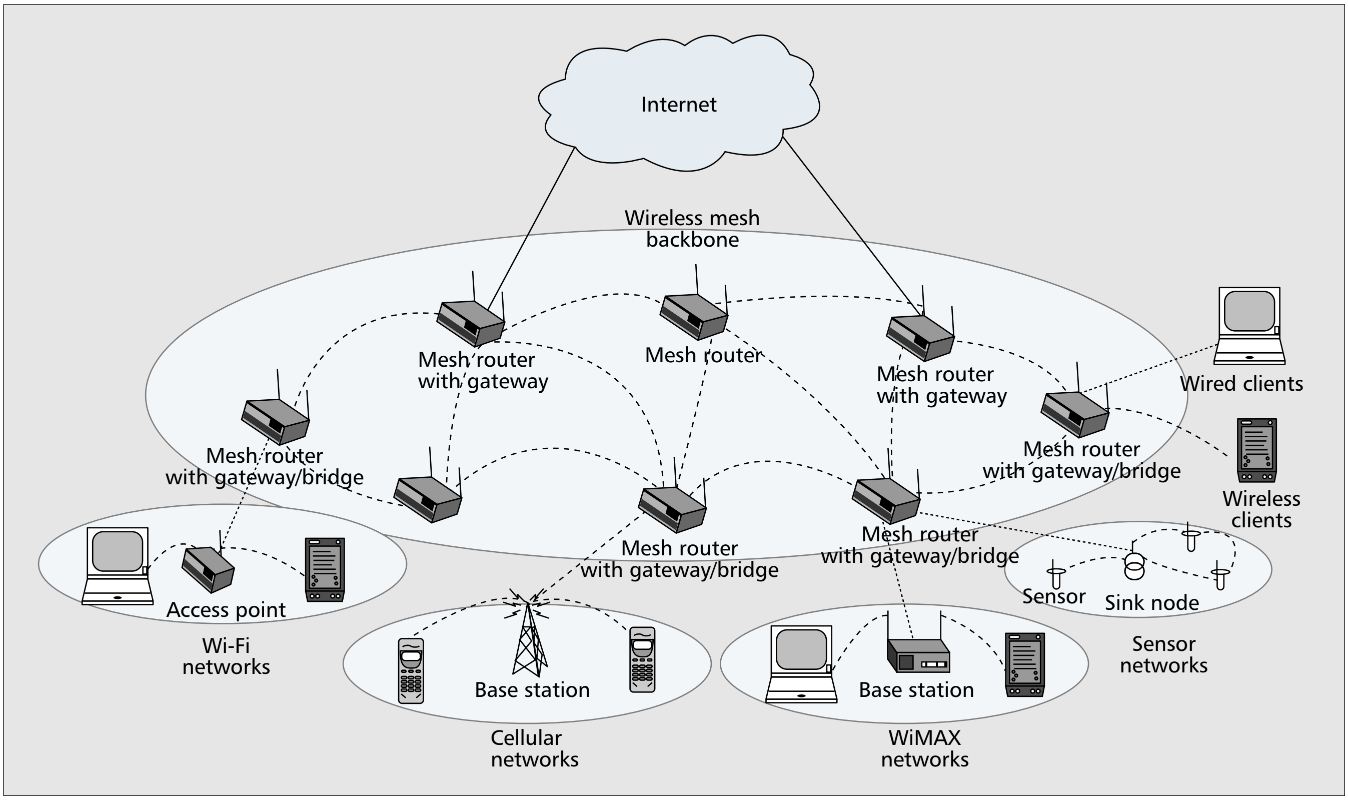

FIGURE 1. *Infrastructure/backbone WMNs.*

formed using one type of radios on devices. Thus, a *Client WMN* is actually the same as a conventional ad hoc network. However, the requirements on end-user devices is increased when compared to infrastructure meshing, since in Client WMNs the end-users must 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. 2. 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.

The characteristics of WMNs are outlined below, where the hybrid architecture is considered for WMNs, since it comprises all the advantages of WMNs:

- WMNs support ad hoc networking, and have the capability of self-forming, self-healing, and self-organization.
- WMNs are multi-hop wireless networks, but with a wireless infrastructure/backbone provided by mesh routers.
- Mesh routers have minimal mobility and perform dedicated routing and configuration, which significantly decreases the load of mesh clients and other end nodes.
- Mobility of end nodes is supported easily through the wireless infrastructure.
- Mesh routers integrate heterogeneous networks, including both wired and wireless. Thus, multiple types of network access exist in WMNs.
- Power-consumption constraints are different for mesh routers and mesh clients.
- WMNs are not stand-alone and need to be compatible and interoperable with other wireless networks.

Therefore, WMNs diversify the capabilities of ad-hoc networks instead of simply being another type of ad hoc network. These additional capabilities necessitate new algorithms and design principles for the realization of WMNs.

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. Although these radio technologies are still in their infancy, they are expected to be the future platform for wireless networks due to their dynamic control capability. 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. For example, routing protocols may not be able to find a reliable routing path, transport protocols may loose connections, and MAC protocols may experience significant throughput reduction. To ensure the scalability in WMNs, all protocols from the MAC layer to the application layer need to be scalable.

Mesh Connectivity. Many advantages of WMNs originate from mesh connectivity. To ensure reliable mesh connectivity, network self-organization and topology control algorithms are needed. Topology-aware MAC and routing protocols can significantly improve the performance of 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 through-

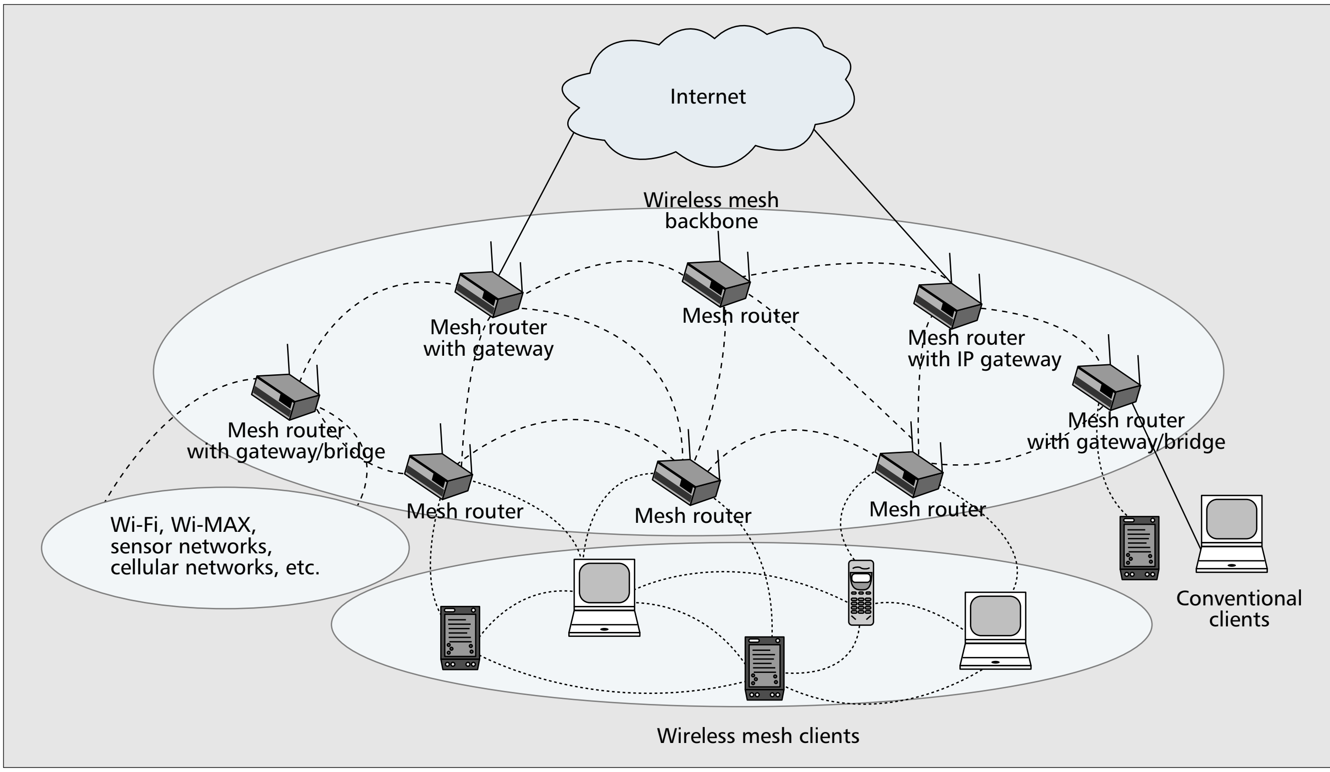

FIGURE 2. *Hybrid WMNs.*

put, 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. Moreover, the different network architectures between WMNs and ad hoc networks usually render a solution for ad hoc networks ineffective in WMNs.

Ease of Use. Protocols must be designed to enable the network to be as autonomous as possible. In addition, network management tools need to be developed to efficiently maintain the operation, monitor the performance, and configure the parameters of WMNs. These tools, together with the autonomous mechanisms in networking protocols, enable rapid deployment of WMNs.

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. This demands that mesh routers need to be capable of integrating heterogeneous wireless networks.

Advances and Research Challenges

The distinct features and critical design factors of WMNs bring many challenging issues to communication protocols, ranging from the physical layer to the application layer. 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.

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 [1], 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 [1]:

- 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 implication given in [1] can also be reflected in [2]. The scheme proposed in [2] 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.

The analytical approaches in [1, 2] have significantly driven the research progress in wireless network capacity. One limitation of these approaches is that the networking protocols have not been appropriately captured. Different medium access control, power control, and routing protocols significantly impact the capacity of a wireless network. However, in the analytical approaches [1, 2], they are only represented by oversimplified models.

Another limitation of existing analytical approaches [1] is that the theoretical capacity bounds are derived based on the asymptotic analysis. These results, however, do not reveal the exact capacity of a network with a given number of nodes, in particular when the number is small. The reason is that the assumptions about the network size or node density in the asymptotic analysis do not match the actual scale of any WMNs; neither network size nor node density will go infinite, no matter how a WMN is deployed. Moreover, due to the differences between WMNs and ad hoc networks, the analytical results of ad hoc networks may not be directly applicable to WMNs. Thus, new analytical results need to be derived for WMNs.

Layered Communication Protocols

Physical Layer

Advanced Physical-Layer Techniques. Some advanced physical-layer techniques have been available for WMNs. 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. For example, mesh networking among multiple nodes makes the system model much more complicated than that of a conventional MIMO system in wireless LANs or cellular networks.

In order to achieve much better spectrum utilization and viable frequency planning for WMNs, frequency-agile or cognitive radios are being developed to dynamically capture the unoccupied spectrum. The FCC has recognized the promising technique and is pushing to enable it to a full realization. Implementing cognitive radios on a software radio platform is one of the most powerful solutions, because all components of a radio, such as RF bands, channel access modes, and channel modulations, are programmable. The software radio platform is not a mature technology yet, although physical testbeds are currently available. However, in the long run it will be a key technology for wireless communications because it can enable the programmability of all advanced physical layer techniques.

Open Research Issues. Open issues in the physical layer are twofold:

- It is necessary to further improve the transmission rate and the performance of physical-layer techniques. New wideband transmission schemes other than OFDM or UWB are needed in order to achieve higher transmission rate in a larger-area network. Multiple-antenna systems have been researched for years. However, their complexity and cost are still too high to be widely accepted for commercialization. Frequency-agile techniques are still in their early phase, and tremendous research efforts are needed before they can be accepted for commercial use.
- To best utilize the advanced features provided by the physical layer, higher-layer protocols, especially MAC protocols, need to work interactively with the physical layer. Consequently, some components in the physical layer must be designed in a way that higher layers can access or control them. This makes hardware design more challenging and also motivates the innovation of low-cost software radio techniques.

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.
- Network self-organization is needed for better collaboration between neighboring nodes and nodes in multi-hop distances.
- 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. For example, in an IEEE 802.11 mesh network, the MAC protocol can be improved by adjusting parameters of CSMA/CA, e.g., contention window size, and modify backoff procedures. However, 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. These schemes also face other difficulties such as cost, system complexity, and practicality of fast steerable directional antennas. 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.

Proposing Innovative MAC Protocols. Because of their poor scalability in a multi-hop network, random access protocols such as CSMA/CA are not an efficient solution. Thus, revisiting the design of MAC protocols based on TDMA or CDMA is indispensable. To date, few TDMA or CDMA MAC protocols are available for WMNs, probably because of two factors. One is the complexity and cost of developing a distributed and cooperative MAC with TDMA or CDMA. The other is the compatibility of TDMA (or CDMA) MAC with existing MAC protocols. For example, in IEEE 802.16, the original MAC protocol is a centralized TDMA scheme, but a distributed TDMA MAC for IEEE 802.16 mesh is still missing. In IEEE 802.11 WMNs, how to design a distributed TDMA MAC protocol overlaying CSMA/CA is an interesting but a challenging problem [3].

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. Depending on hardware platforms, different multi-channel MAC protocols need to be developed.

Multi-Channel Single-Transceiver MAC. If cost and compatibility are the concern, one transceiver on a radio is a preferred hardware platform. Since only one transceiver is available, only one channel is active at a time in each network node. However, different nodes may operate on different channels simultaneously. To coordinate transmissions between network nodes under this situation, protocols such as the multi-channel MAC in [4] are needed.

Multi-Channel Multi-Transceiver MAC. In this scenario, a radio includes multiple parallel RF front-end chips and baseband processing modules to support several simultaneous channels. On top of the physical layer, only one MAC layer module is needed to coordinate the functions of multiple channels. To the best of our knowledge, so far no multi-channel multi-transceiver MAC protocol has been proposed for WMNs.

Multi-Radio MAC. In this scenario, a network node has multiple radios each with its own MAC and physical layers.

Communications in these radios are totally independent. Thus, a virtual MAC protocol such as the multi-radio unification protocol (MUP) [5] is required on top of MAC to coordinate communications in all channels. In fact, one radio can have multiple channels in this case. However, for simplicity of design and application, a single fixed channel is usually applied in each radio.

Open Research Issues. There exist the following major challenging issues.

Scalable MAC. To the best of our knowledge, the scalability issue in multi-hop ad hoc networks has not been fully solved yet. Most existing MAC protocols only solve partial problems of the overall issue, but raise other problems. To make the MAC protocol really scalable, new distributed and collaborative schemes must be proposed to ensure that network performance (e.g., throughput and even QoS parameters such as delay and delay jitter) will not degrade as network size increases. It is obvious that a multi-channel MAC protocol can achieve higher throughput than a single-channel MAC. However, to really achieve spectrum efficiency and improve the per-channel throughput, the scalable MAC protocol needs to consider the overall performance improvement in multiple channels. Thus, developing a scalable multi-channel MAC is a more challenging task than a single-channel MAC.

MAC/Physical Cross-Layer Design. When advanced physical layer techniques, such as MIMO and cognitive radios, are used, novel MAC protocols, especially multi-channel MAC, need to be proposed to utilize the agility provided by the physical layer.

Network Integration in the MAC Layer. Mesh routers in WMNs are responsible for the integration of various wireless technologies. Thus, advanced bridging functions must be developed in the MAC layer so that different wireless radios, such as IEEE 802.11, 802.16, 802.15, etc., can seamlessly work together. Reconfigurable/software radios and the related radio resource management schemes may be the ultimate solution to these bridging functions.

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. We believe that 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. With the mesh infrastructure provided by mesh routers, the routing protocol for mesh clients can also be made simple.

Existing routing protocols for ad hoc networks have already considered some of these features. However, none of them has captured all of these features, as explained in the following routing protocols.

Routing Protocols with Various Performance Metrics. The impact of performance metrics on a routing protocol is studied in [6] 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 [6] are still not enough for WMNs when mobility is concerned.

Multi-Radio Routing. A multi-radio LQSR (MR-LQSR) is proposed in [7], 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 trade-off 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. The main objectives of using multi-path routing are 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.

Hierarchical Routing. In hierarchical routing [8], a certain self-organization scheme is employed to group network nodes into clusters. Each cluster has one or more cluster heads. Nodes in a cluster can be one or more hops away from the cluster head. Since connectivity between clusters is needed, some nodes can communicate with more than one cluster and work as a gateway. When the node density is high, hierarchical routing protocols tend to achieve much better performance because of less overhead, shorter average routing path, and quicker set-up procedure of routing path. However, the complexity of maintaining the hierarchy may compromise the performance of the routing protocol. Moreover, in WMNs, a mesh client must avoid being a cluster head because it can become a bottleneck due to its limited capability.

Geographic Routing. Compared to topology-based routing schemes, geographic routing schemes forward packets by only using the position information of nodes in the vicinity and the destination node [9]. Thus, topology change has less impact on the geographic routing than the other routing protocols. Early geographic routing algorithms are a type of single-path greedy routing schemes in which the packet forwarding decision is made based on the location information of the current forwarding node, its neighbors, and the destination node. However, all greedy routing algorithms have a common problem, i.e., delivery is not guaranteed even if a path exists between source and destination. In order to guarantee delivery, planar-graph-based geographic routing algorithms [9] have been proposed recently. However, these algorithms usually have much higher communication overhead than the single-path greedy routing algorithms.

Open Research Issues. For a routing protocol of WMNs, several research issues still remain unresolved.

Scalability. Hierarchical routing protocols can only partially solve this problem due to their complexity and difficulty of management. Geographic routing relies on the existence of

GPS or similar positioning technologies, which increases cost and complexity of WMNs. Thus, new scalable routing protocols need to be developed.

Better Performance Metrics. New performance metrics need to be developed. Also, it is necessary to integrate multiple performance metrics into a routing protocol so that the optimal overall performance is achieved.

Routing/MAC Cross-Layer Design. A routing protocol needs to interact with the MAC layer in order to improve its performance. Adopting multiple performance metrics from layer-2 into routing protocols is an example. However, interaction between MAC and routing layers is so close that merely exchanging parameters between them is not adequate. Merging certain functions of MAC and routing protocols is a promising approach.

Efficient Mesh Routing. With the mesh infrastructure, a much simpler and more efficient routing protocol than an ad hoc network routing protocol needs to be developed for WMNs.

Transport Layer

To date, no transport protocol has been proposed specifically for WMNs. However, a large number of transport protocols are available for ad hoc networks. Studying these protocols helps in the design of transport protocols for WMNs.

Different transport protocols are needed for non-real-time and real-time traffic.

Reliable Data Transport. Reliable transport protocols can be further classified into two types: TCP variants and new transport protocols.

TCP variants improve the performance of the classical TCPs by tackling the following problems.

Non-Congestion Packet Losses. The classical TCPs do not differentiate congestion and non-congestion losses. As a result, when non-congestion losses occur, the network throughput quickly drops due to unnecessary congestion avoidance. In addition, when wireless channels return to normal operation, the classical TCP cannot be recovered quickly. A feedback mechanism can be used to differentiate different packet losses.

Unknown Link Failure. Link failure occurs frequently in mobile ad hoc networks, since all nodes are mobile. As far as WMNs are concerned, link failure is not as critical as in mobile ad hoc networks, because the WMN infrastructure avoids the issue of single-point-of-failure. However, due to wireless channels and mobility in mesh clients, link failure may still happen. To enhance TCP performance, link failure needs to be detected.

Network Asymmetry. Network asymmetry is defined as the situation in which the forward direction of a network is significantly different from the reverse direction in terms of bandwidth, loss rate, and latency. Thus, it impacts the transmission of ACKs. Since TCP is critically dependent on ACK, its performance can be severely degraded by network asymmetry. Although schemes such as ACK filtering, ACK congestion control, etc. help to solve the network asymmetry problem, whether they are applicable to WMNs needs investigation.

Large RTT Variations. Considering mobility, variable link quality, fluctuating traffic load, and other factors in WMNs, the change of routing path may be frequent and may cause large variations of RTT. This will degrade the TCP performance, because the normal operation of TCP relies on a smooth measurement of RTT.

To further improve performance of transport protocols, researchers have started to develop entirely new transport protocols. In [10], the ad hoc transport protocol (ATP) is proposed for ad hoc networks. Transmissions in ATP are rate-based, and quick-start is used for initial rate estimation. Congestion detection is a delay-based approach, and thus ambiguity between congestion losses and non-congestion losses is avoided. Moreover, in ATP there is no retransmission timeout, and congestion control and reliability are decoupled. New transport protocols such as ATP achieve much better performance (e.g., delay, throughput, and fairness) than the TCP variants. However, for WMNs an entirely new transport protocol is not a favorable solution. WMNs will be integrated with the Internet and many other wireless networks, and thus transport protocols for WMNs need to be compatible with TCPs.

Real-Time Delivery. To support end-to-end delivery of real-time traffic, a rate control protocol (RCP) is needed to work with UDP. Although many RCPs are proposed for wired networks, no schemes are available for WMNs. Recently, an adaptive detection rate control (ADTFRC) scheme has been proposed for mobile ad hoc networks in [11], where an end-to-end multi-metric joint detection approach is developed for TCP-friendly rate control schemes. However, to really support real-time delivery for multimedia traffic, the accuracy of the detection approach is still insufficient. In addition, all non-congestion packet losses due to different problems are processed in the same way [11], which may degrade the performance of the rate control scheme.

Open Research Issues. For reliable transport in WMNs, in addition to better solutions to the above mentioned problems, several other issues need further investigation.

Cross-layer Solution to Network Asymmetry. All problems of TCP performance degradation are actually related to protocols in the lower layers. For example, it is the routing protocol that determines the path for both TCP data and ACK packets. To avoid asymmetry between data and ACK packets, it is desired that a routing protocol selects an optimal path for both data and ACK packets. Moreover, the link-layer performance directly impacts the packet loss ratio. In order to reduce the possibility of network asymmetry, MAC and error control need to treat TCP data and ACK packets differently.

Adaptive TCP. WMNs will also be integrated with the Internet and various wireless networks such as IEEE 802.11, 802.16, 802.15, etc. The heterogeneity among these networks renders the same TCP ineffective for all networks. Applying different TCPs in different networks is a complicated and costly approach. As a result, adaptive TCP is the most promising solution. Thus, adaptive transport protocols need to be proposed for WMNs.

For real-time transport, entirely new RCPs need to be developed by considering the features of WMNs. In addition, new loss differentiation schemes must be developed to work together with RCPs. Since WMNs will be integrated with various wireless networks and the Internet, adaptive rate control protocols are also needed.

Application Layer

Numerous applications supported by WMNs can be categorized into several classes.

Internet Access. Various Internet applications provide important timely information to people, make life more convenient, and increase work efficiency and productivity. In a home or small to medium business environment, the most popular network access solution is still DSL or cable modem along with IEEE 802.11 access points. However, compared with this approach, WMNs have many potential advantages: lower cost, higher speed, and easier installation.

Distributed Information Storage and Sharing. Backhaul access to the Internet is not necessary in this type of applications, and users only communicate within WMNs. A user may want to store high-volume data in disks owned by other users, download files from other users' disks based on peer-to-peer networking mechanisms, and query/retrieve information located in distributed database servers. Users within WMNs may also want to chat, talk on video phones, and play games with each other.

Information Exchange across Multiple Wireless Networks. For example, a cellular phone may want to talk to a Wi-Fi phone through WMNs, or a user on a Wi-Fi network may expect to monitor the status in various sensors in a wireless sensor networks. Consequently, there are mainly three research directions in the application layer.

Improve Existing Application Layer Protocols. In a wireless network, protocols in the lower layers cannot provide perfect support for the application layer. For example, as perceived by the application layer, packet loss may not always be zero, packet delay may be variable with a large jitter, etc. These problems become more severe in WMNs due to their ad hoc and multi-hop communications. Such problems can fail many Internet applications that work smoothly in a wired network.

Propose New Application-Layer Protocols for Distributed Information Sharing. Currently, many peer-to-peer protocols are available for information sharing on the Internet. However, these protocols cannot achieve satisfactory performance in WMNs since WMNs have much different characteristics than the Internet.

Develop Innovative Applications for WMNs. Such applications must bring tremendous benefits to users, and also cannot achieve best performance without WMNs. Such applications will enable WMNs to be a unique networking solution instead of just another option for wireless networking.

Network Management

Many management functions are needed to maintain the appropriate operation of WMNs.

Mobility Management. A distributed mobility management scheme is needed for WMNs. However, because of the existence of a backbone network, a distributed scheme for WMNs can be simpler than that for mobile ad hoc networks. How to take advantage of the network backbone to design a lightweight distributed mobility management scheme for WMNs needs further investigation. Mobility management is closely related to multiple layers of network protocols, so developing multi-layer mobility management schemes is another interesting research topic.

Location service is a desired feature by WMNs. Location information can enhance the performance of MAC and routing protocols, and it can help to develop promising location-related applications. Proposing accurate or efficient algorithms for location service is still an open research topic.

Power Management. The goal of power management in WMNs varies with network nodes. Usually, mesh routers do not have a constraint on power consumption; power management aims to control connectivity, interference, spectrum spatial-reuse, and topology. In contrast to mesh routers, mesh clients may expect protocols to be power-efficient. Thus, it is quite possible that WMNs require power management to optimize both power efficiency and connectivity, which results in a complicated problem.

Network Monitoring. Many functions are performed in a network management protocol. The statistics in the management information base (MIB) of mesh nodes, especially mesh routers, need to be reported to one or several servers in order to continuously monitor network performance. In addition, data processing algorithms in the performance monitoring software on the server analyze these statistical data and determine potential abnormalities. Based on the statistical information collected from the MIB, data processing algorithms can also accomplish many other functions such as network topology monitoring.

Several research issues exist in network monitoring. To reduce overhead, efficient transmission of network monitoring information in a mesh network topology is expected. In addition, in order to accurately detect abnormal operation and quickly derive a multihop mesh network topology of WMNs, new data processing algorithms need to be developed.

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. The attacker may sneak into the network, impersonate a legitimate node, and not follow the required specifications of a routing protocol. The same types of attacks as in routing protocols may also occur in MAC protocols. For example, the backoff procedures and NAV for virtual carrier sense of IEEE 802.11 MAC may be misused by some attacking nodes, which causes the network to always be congested by these malicious nodes. 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. However, AAA is performed through a centralized server such as RADIUS (remote authentication dial-in user service). Such a centralized scheme is not applicable in WMNs. Moreover, security key management in WMNs is much more difficult than in wireless LANs, because there is no 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. How to design and implement a practical security system, including cross-layer secure network protocols and various intrusion detection algorithms, is a challenging research topic.

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, as discussed before in the open research issues of different protocol layers.

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. As another example, the physical layer can report link quality to a routing protocol as an additional performance metric for routing algorithms. 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.

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.

Scalability. 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.

Security. 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, we believe that WMNs will be one of the most promising technologies for next-generation wireless networking.

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