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Wireless mesh networks: a survey

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Abstract

Wireless mesh networks (WMNs) consist of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of WMNs. They provide network access for both mesh and conventional clients. The integration of WMNs with other networks such as the Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks, etc., can be accomplished through the gateway and bridging functions in the mesh routers. Mesh clients can be either stationary or mobile, and can form a client mesh network among themselves and with mesh routers. WMNs are anticipated to resolve the limitations and to significantly improve the performance of ad hoc networks, wireless local area networks (WLANs), wireless personal area networks (WPANs), and wireless metropolitan area networks (WMANs). They are undergoing rapid progress and inspiring numerous deployments. WMNs will deliver wireless services for a large variety of applications in personal, local, campus, and metropolitan areas. Despite recent advances in wireless mesh networking, many research challenges remain in all protocol layers. This paper presents a detailed study on recent advances and open research issues in WMNs. System architectures and applications of WMNs are described, followed by discussing the critical factors influencing protocol design. Theoretical network capacity and the state-of-the-art protocols for WMNs are explored with an objective to point out a number of open research issues. Finally, testbeds, industrial practice, and current standard activities related to WMNs are highlighted.

Keywords: Wireless mesh networks; Ad hoc networks; Wireless sensor networks; Medium access control; Routing protocol; Transport protocol; Scalability; Security; Power management and control; Timing synchronization

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1. Introduction

As various wireless networks evolve into the next generation to provide better services, a key technology, wireless mesh networks (WMNs), has emerged recently. In WMNs, nodes are comprised of mesh routers and mesh clients. Each node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage.

Conventional nodes (e.g., desktops, laptops, PDAs, PocketPCs, phones, etc.) equipped with wireless network interface cards (NICs) can connect directly to 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 the users to be always-on-line anywhere anytime. Moreover, the gateway/bridge functionalities in mesh routers enable the integration of WMNs with various existing wireless networks such as cellular, wireless sensor, wireless-fidelity (Wi-Fi) [136], worldwide inter-operability for microwave access (WiMAX) [137], WiMedia [138] networks. Consequently, through an integrated WMN, the users of existing network can be provided with otherwise impossible services of these networks.

WMN is a promising wireless technology for numerous applications [98], e.g., broadband home networking, community and neighborhood networks, enterprise networking, building automation, etc. It is gaining significant attention as a possible way for cash strapped Internet service providers (ISPs), carriers, and others to roll out robust and reliable wireless broadband service access in a way that needs minimal up-front investments. With the capability of self-organization and self-configuration, WMNs can be deployed incrementally, one node at a time, as needed. As more nodes are installed, the reliability and connectivity for the users increase accordingly.

Deploying a WMN is not too difficult, because all the required components are already available in the form of ad hoc network routing protocols, IEEE 802.11 MAC protocol, wired equivalent privacy (WEP) security, etc. 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, to make a WMN be all it can be, considerable research efforts are still needed. For example, the available MAC and routing protocols applied to WMNs do not have enough scalability; the throughput drops significantly as the number of nodes or hops in a WMN increases. Similar problems exist in other networking protocols. Consequently, all existing protocols from the application layer to transport, network MAC, and physical layers need to be enhanced or re-invented.

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 WMNs. Industrial standards groups are also actively working on new specifications for mesh networking. For example, IEEE 802.11 [64,74], IEEE 802.15 [65,79], and IEEE 802.16 [66,111,135] all have established sub-working groups to focus on new standards for WMNs.

The remainder of the paper is organized as follows. In Section 2, we present possible system architectures of WMNs. The characteristics of WMNs are summarized in Section 3, where a comparison between WMNs and ad hoc networks is also conducted. In Section 4, different application scenarios of WMNs are addressed. Critical factors influencing protocol design are emphasized in Section 5. We discuss fundamental issues such as network capacity and optimal node density of WMNs in Section 6. Recent advances in protocol design for WMNs are investigated in Sections 7–15, where protocols on both data and management planes are covered and challenging research issues in all these aspects are discussed. Several testbeds and implementation practice of WMNs are pre-

sented in Section 16. Current status of standard activities in WMNs is highlighted in Section 17. The paper is concluded in Section 18.

2. Network architecture

WMNs consist of two types of nodes: mesh routers and mesh clients. Other than the routing capability for gateway/repeater functions as in a conventional wireless router, a wireless mesh router contains additional routing functions to support mesh networking. 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. Compared with a conventional wireless router, a wireless mesh router can achieve the same coverage with much lower transmission power through multi-hop communications. Optionally, the medium access control (MAC) protocol in a mesh router is enhanced with better scalability in a multi-hop mesh environment.

In spite of all these differences, mesh and conventional wireless routers are usually built based on a similar hardware platform. Mesh routers can be built based on dedicated computer systems (e.g., embedded systems) and look compact, as shown in Fig. 1. They can also be built based on general-purpose computer systems (e.g., laptop/desktop PC).

Mesh clients also have necessary functions for mesh networking, and thus, can also work as a router. However, gateway or bridge functions do not exist in these nodes. In addition, mesh clients usually have only one wireless interface. As a consequence, the hardware platform and the software for mesh clients can be much simpler than those for mesh routers. Mesh clients have a higher variety of devices compared to mesh routers. They can be a laptop/desktop PC, pocket PC, PDA, IP phone, RFID reader, BACnet (building automation and control networks) controller, and many other devices, as shown in Fig. 2.

The architecture of WMNs can be classified into three main groups based on the functionality of the nodes:

- *Infrastructure/Backbone WMNs*. The architecture is shown in Fig. 3, where dash and solid lines indicate wireless and wired links, respectively. This type of WMNs includes mesh routers forming an infrastructure for clients that connect to them. 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

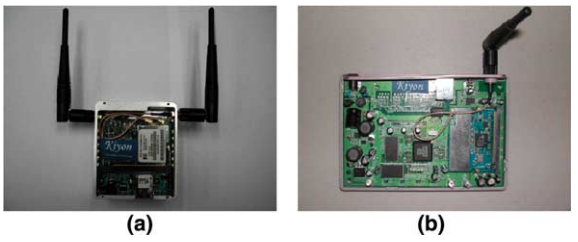

Fig. 1. Examples of mesh routers based on different embedded systems: (a) PowerPC and (b) Advanced Risc Machines (ARM).

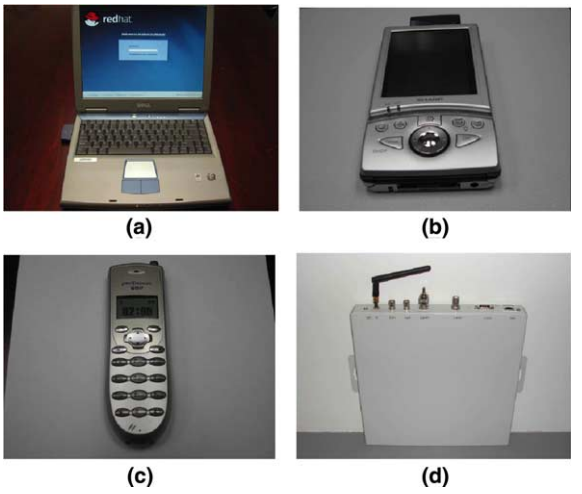

Fig. 2. Examples of mesh clients: (a) Laptop, (b) PDA, (c) Wi-Fi IP Phone and (d) Wi-Fi RFID Reader.

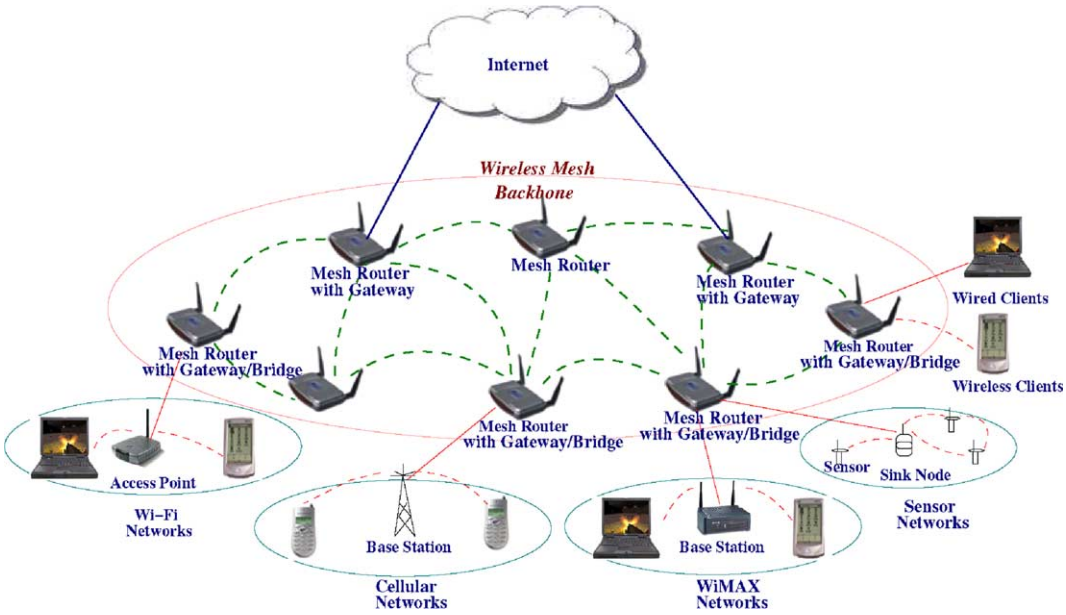

Fig. 3. Infrastructure/backbone WMNs.

infrastructure meshing, provides backbone for conventional clients and enables integration of WMNs with existing wireless networks, through gateway/bridge functionalities in mesh routers. Conventional clients with 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 the base stations that have Ethernet connections to mesh routers.

Infrastructure/Backbone WMNs are the most commonly used type. For example, community and neighborhood networks can be built using *infrastructure meshing*. The mesh routers are placed on the roof of houses in a neighborhood, which serve as access points for users inside the homes and along the roads. Typically, two types of radios are used in the routers, i.e., for backbone communication and for user communication, respectively. The mesh backbone communication can be established using long-range communication techniques including directional antennas.

- *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. The basic architecture is shown in Fig. 4. In *Client WMNs*, a packet destined to a node in the network hops through multiple nodes to reach the destination. *Client WMNs* are usually formed using one type of radios on devices. Moreover, the requirements on end-user devices is increased when compared to *infrastructure meshing*, since, in *Client WMNs*, the end-users

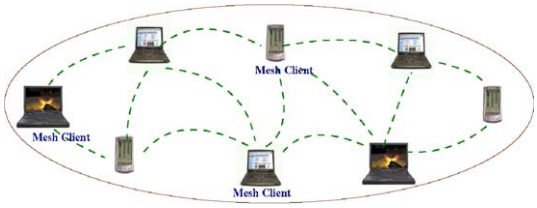

Fig. 4. Client WMNs.

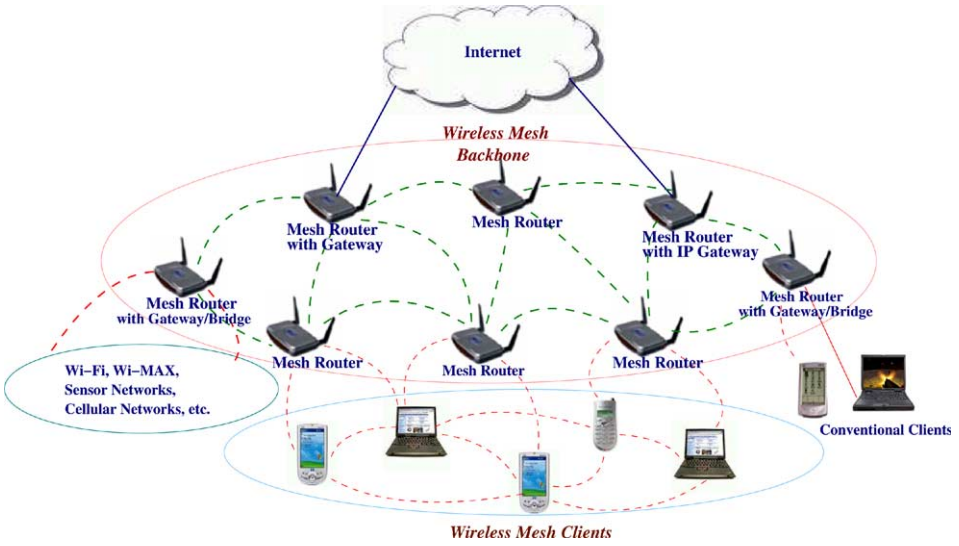

Fig. 5. Hybrid WMNs.

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. 5. 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 the WMN. The hybrid architecture will be the most applicable case in our opinion.

3. Characteristics

The characteristics of WMNs are explained as follows:

- *Multi-hop wireless network*. An objective to develop WMNs is to extend the coverage range of current wireless networks without sacrificing the channel capacity. Another objective is to provide non-line-of-sight (NLOS) connectivity among the users without direct line-of-sight (LOS) links. To meet these requirements, the mesh-style multi-hopping is indispensable [85], which achieves higher throughput without sacrificing effective radio range via shorter link distances, less interference between the nodes, and more efficient frequency re-use.
- *Support for ad hoc networking, and capability of self-forming, self-healing, and self-organization*. WMNs enhance network performance, because of flexible network architecture, easy deployment and configuration, fault tolerance, and mesh connectivity, i.e., multipoint-to-multipoint communications [128]. Due to these features, WMNs have low upfront investment requirement, and the network can grow gradually as needed.
- *Mobility dependence on the type of mesh nodes*. Mesh routers usually have minimal mobility, while mesh clients can be stationary or mobile nodes.
- *Multiple types of network access*. In WMNs, both backhaul access to the Internet and peer-to-peer (P2P) communications are supported [75]. In addition, the integration of WMNs with other wireless networks and providing services to end-users of these networks can be accomplished through WMNs.

- *Dependence of power-consumption constraints on the type of mesh nodes*. Mesh routers usually do not have strict constraints on power consumption. However, mesh clients may require power efficient protocols. As an example, a mesh-capable sensor [113,114] requires its communication protocols to be power efficient. Thus, the MAC or routing protocols optimized for mesh routers may not be appropriate for mesh clients such as sensors, because power efficiency is the primary concern for wireless sensor networks [8,9].
- *Compatibility and interoperability with existing wireless networks*. For example, WMNs built based on IEEE 802.11 technologies [133,69] must be compatible with IEEE 802.11 standards in the sense of supporting both mesh-capable and conventional Wi-Fi clients. Such WMNs also need to be inter-operable with other wireless networks such as WiMAX, ZigBee [148], and cellular networks.

Based on their characteristics, WMNs are generally considered as a type of ad-hoc networks due to the lack of wired infrastructure that exists in cellular or Wi-Fi networks through deployment of base stations or access points. While ad hoc networking techniques are required by WMNs, the additional capabilities necessitate more sophisticated algorithms and design principles for the realization of WMNs. More specifically, instead of being a type of ad-hoc networking, WMNs aim to diversify the capabilities of ad hoc networks. Consequently, ad hoc networks can actually be considered as a *subset* of WMNs. To illustrate this point, the differences between WMNs and ad hoc networks are outlined below. In this comparison, the hybrid architecture is considered, since it comprises all the advantages of WMNs.

- *Wireless infrastructure/backbone*. As discussed before, WMNs consist of a wireless backbone with mesh routers. The wireless backbone provides large coverage, connectivity, and robustness in the wireless domain. However, the connectivity in ad hoc networks depends on the individual contributions of end-users which may not be reliable.
- *Integration*. WMNs support conventional clients that use the same radio technologies as a mesh router. This is accomplished through a host-routing function available in mesh routers. WMNs also enable integration of various existing networks such as Wi-Fi, the Internet, cellular and sensor networks through gateway/bridge functionalities in the mesh routers. Consequently, users in one network are provided with services in other networks, through the use of the wireless infrastructure. The integrated wireless networks through WMNs resembles the Internet backbone, since the physical location of network nodes becomes less important than the capacity and network topology.
- *Dedicated routing and configuration*. In ad hoc networks, end-user devices also perform routing and configuration functionalities for all other nodes. However, WMNs contain mesh routers for these functionalities. Hence, the load on end-user devices is significantly decreased, which provides lower energy consumption and high-end application capabilities to possibly mobile and energy constrained end-users. Moreover, the end-user requirements are limited which decreases the cost of devices that can be used in WMNs.
- *Multiple radios*. As discussed before, mesh routers can be equipped with multiple radios to perform routing and access functionalities. This enables separation of two main types of traffic in the wireless domain. While routing and configuration are performed between mesh routers, the access to the network by end users can be carried out on a different radio. This significantly improves the capacity of the network. On the other hand, in ad hoc networks, these functionalities are performed in the same channel, and as a result, the performance decreases.
- *Mobility*. Since ad hoc networks provide routing using the end-user devices, the network topology and connectivity depend on the movement of users. This imposes additional challenges on routing protocols as well as on network configuration and deployment.

4. Application scenarios

Research and development of WMNs is motivated by several applications which clearly demonstrate the promising market while at the same time these applications cannot be supported directly by other wireless networks such as cellular networks, ad hoc networks, wireless sensor networks, standard IEEE 802.11, etc. In this section, we discuss these applications.

- *Broadband home networking*. Currently broadband home networking is realized through IEEE 802.11 WLANs. An obvious problem is the location of the access points. Without a site survey, a home (even a small one) usually has many dead zones without service coverage. Solutions based on site survey are expensive and not practical for home networking, while installation of multiple access points is also expensive and not convenient because of Ethernet wiring from access points to backhaul network access modem or hub. Moreover, communications between end nodes under two different access points have to go all the way back to the access hub. This is obviously not an efficient solution, especially for broadband networking. Mesh networking, as shown in Fig. 6, can resolve all these issues in home networking.
  The access points must be replaced by wireless mesh routers with mesh connectivity established among them. Therefore, the communication between these nodes becomes much more flexible and more robust to network faults and link failures. Dead zones can be eliminated by adding mesh routers, changing locations of mesh routers, or automatically adjusting power levels of mesh routers. Communication within home networks can be realized through mesh networking without going back to the access hub all the time. Thus, network congestion due to backhaul access can be avoided. In this application, wireless mesh routers have no constraints on power consumptions and mobility. Thus, protocols proposed for mobile ad hoc networks [34] and wireless sensor networks [8,9] are too cumbersome to achieve satisfactory performance in this application. On the other hand, Wi-Fi's are not capable of supporting ad hoc multi-hop networking. As a consequence, WMNs are well-suited for broadband home networking.
- *Community and neighborhood networking*. In a community, the common architecture for network access is based on cable or DSL connected to the Internet, and the last-hop is wireless by connecting a wireless router to a cable or DSL modem. This type of network access has several drawbacks:
  - Even if the information must be shared within a community or neighborhood, all traffic must flow through Internet. This significantly reduces network resource utilization.
  - Large percentage of areas in between houses is not covered by wireless services.
  - An expensive but high bandwidth gateway between multiple homes or neighborhoods may not be shared and wireless services must be set up individually. As a result, network service costs may increase.
  - Only a single path may be available for one home to access the Internet or communicate with neighbors.

  WMNs mitigate the above disadvantages through flexible mesh connectivities between homes, as shown in Fig. 7. WMNs can also enable many applications such as distributed file storage, distributed file access, and video streaming.

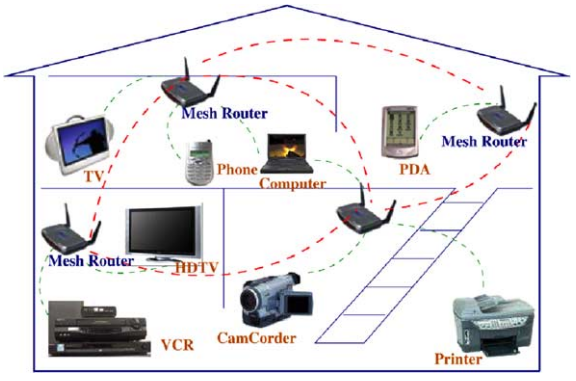

Fig. 6. WMNs for broadband home networking.

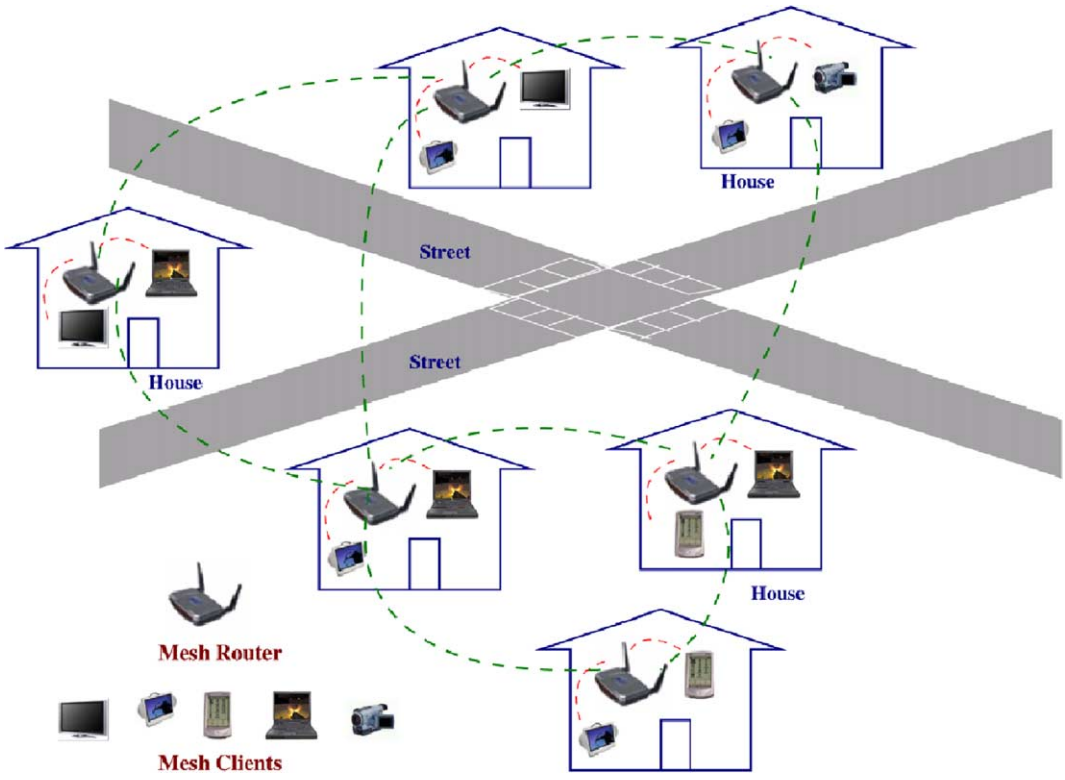

Fig. 7. WMNs for community networking.

- *Enterprise networking*. This can be a small network within an office or a medium-size network for all offices in an entire building, or a large scale network among offices in multiple buildings. Currently, standard IEEE 802.11 wireless networks are widely used in various offices. However, these wireless networks are still isolated islands. Connections among them have to be achieved through wired Ethernet connections, which is the key reason for the high cost of enterprise networks. In addition, adding more backhaul access modems only increases capacity locally, but does not improve robustness to link failures, network congestion and other problems of the entire enterprise network. If the access points are replaced by mesh routers, as shown in Fig. 8, Ethernet wires can be eliminated. Multiple backhaul access modems can be shared by all nodes in the entire network, and thus, improve the robustness and resource utilization of enterprise networks. WMNs can grow easily as the size of enterprise expands. WMNs for enterprise networking are much more complicated than at home because more nodes and more complicated network topologies are involved. The service model of enterprise networking can be applied to many other public and commercial service networking scenarios such as airports, hotels, shopping malls, convention centers, sport centers, etc.
- *Metropolitan area networks*. WMNs in metropolitan area have several advantages. The physical-layer transmission rate of a node in WMNs is much higher than that in any cellular networks. For example, an IEEE 802.11g node can transmit at a rate of 54% Mbps. Moreover, the communication between nodes in WMNs does not rely on a wired backbone. Compared to wired networks, e.g., cable or optical networks, wireless mesh MAN is an economic

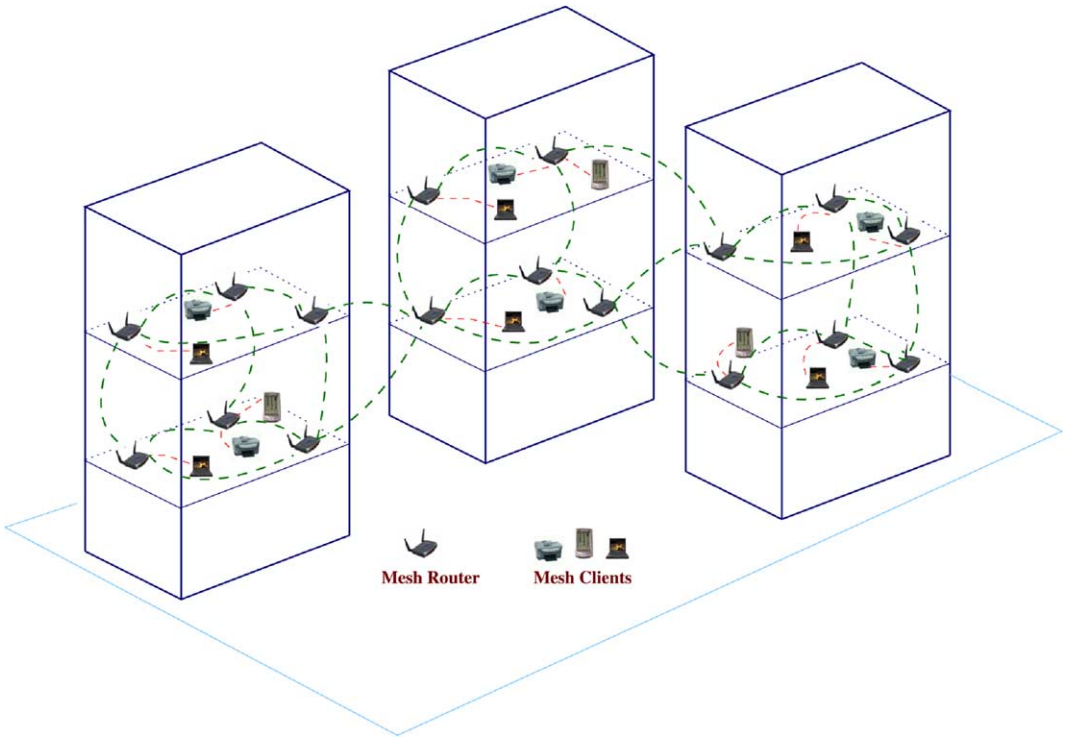

Fig. 8. WMNs for enterprise networking.

alternative to broadband networking, especially in underdeveloped regions. Wireless mesh MAN covers a potentially much larger area than home, enterprise, building, or community networks, as shown Fig. 9. Thus, the requirement on the network scalability by wireless mesh MAN is much higher than that by other applications.

- *Transportation systems*. Instead of limiting IEEE 802.11 or 802.16 access to stations and stops, mesh networking technology can extend access into buses, ferries, and trains. Thus, convenient passenger information services, remote monitoring of in-vehicle security video, and driver communications can be supported. To enable such mesh networking for a transportation system, two key techniques are needed: the high-speed mobile backhaul from a vehicle (car, bus, or train) to the Internet and mobile mesh networks within the vehicle, as shown in Fig. 10.
- *Building automation*. In a building, various electrical devices including power, light, elevator, air conditioner, etc., need to be controlled and monitored. Currently this task is accomplished through standard wired networks, which is very expensive due to the complexity in deployment and maintenance of a wired network. Recently Wi-Fi based networks have been adopted to reduce the cost of such networks. However, this effort has not achieved satisfactory performance yet, because deployment of Wi-Fi's for this application is still rather expensive due to wiring of Ethernet. If BACnet (building automation and control networks) access points are replaced by mesh routers, as shown in Fig. 11, the deployment cost will be significantly reduced. The deployment process is also much simpler due to the mesh connectivity among wireless routers.
- *Health and medical systems*. In a hospital or medical center, monitoring and diagnosis data

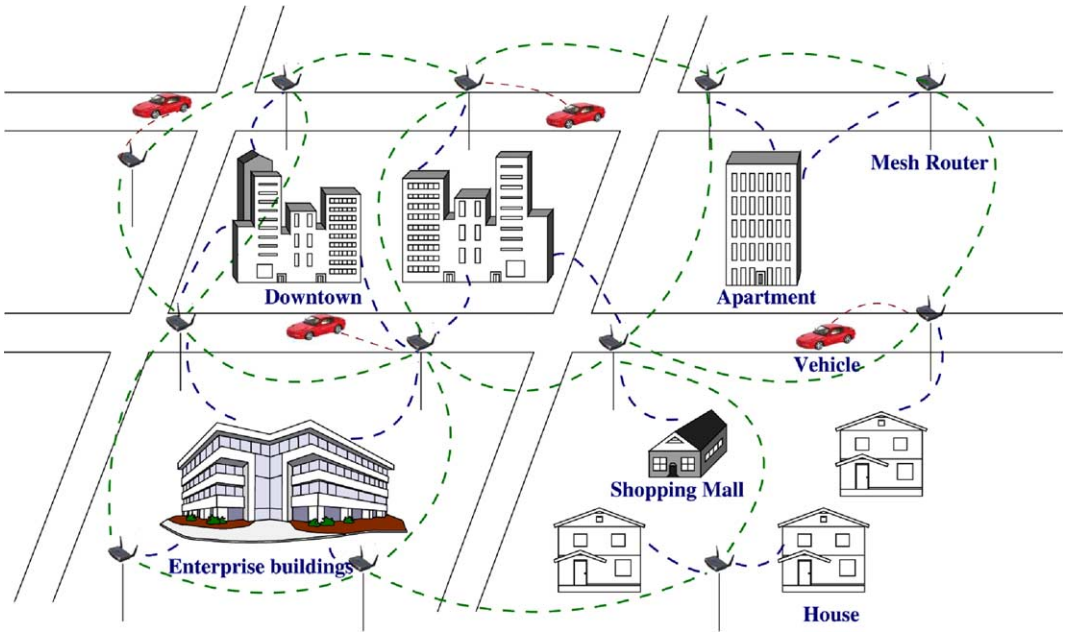

Fig. 9. WMNs for metropolitan area networks.

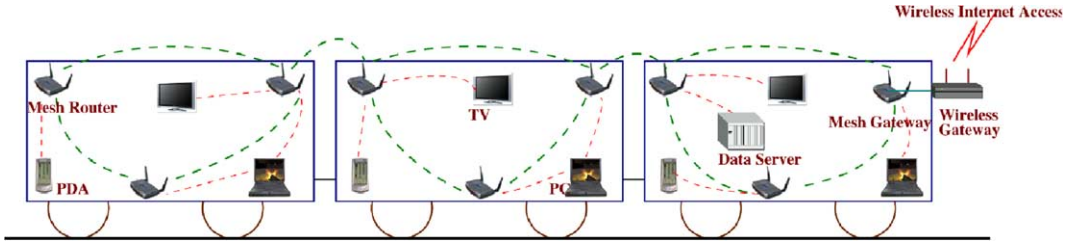

Fig. 10. WMNs for transportation systems.

need to be processed and transmitted from one room to another for various purposes. Data transmission is usually broadband, since high resolution medical images and various periodical monitoring information can easily produce a constant and large volume of data. Traditional wired networks can only provide limited network access to certain fixed medical devices. Wi-Fi based networks must rely on the existence of Ethernet connections, which may cause high system cost and complexity but without the abilities to eliminate dead spots. However, these issues do not exist in WMNs.

- *Security surveillance systems*. As security is turning out to be a very high concern, security surveillance systems become a necessity for enterprise buildings, shopping malls, grocery stores, etc. In order to deploy such systems at locations as needed, WMNs are a much more viable solution than wired networks to connect all devices. Since still images and videos are the major traffic flowing in the network, this application demands much higher network capacity than other applications.

In addition to the above applications, WMNs can also be applied to *Spontaneous* (*Emergency*/

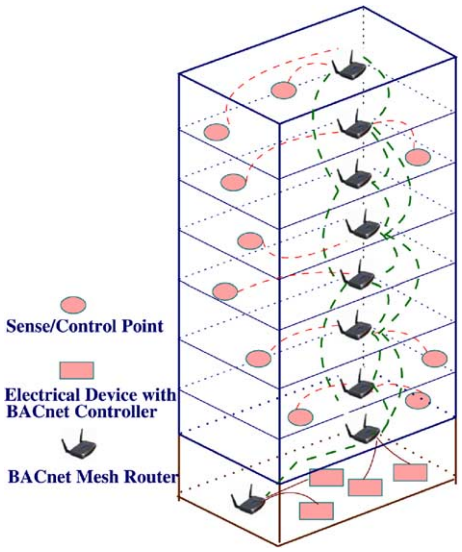

Fig. 11. WMNs for building automation.

Disaster) *Networking* and *P2P Communications*. For example, wireless networks for an emergency response team and firefighters do not have in-advance knowledge of where the network should be deployed. By simply placing wireless mesh routers in desired locations, a WMN can be quickly established. For a group of people holding devices with wireless networking capability, e.g., laptops and PDAs, P2P communication anytime anywhere is an efficient solution for information sharing. WMNs are able to meet this demand. These Applications illustrate that WMNs are a superset of ad hoc networks, and thus can accomplish all functions provided by ad hoc networking.

5. Critical factors influencing network performance

Before a network is designed, deployed, and operated, factors that critically influence its performance need to be considered. For WMNs, the critical factors are summarized as follows:

- *Radio techniques.* Driven by the rapid progress of semiconductor, RF technologies, and communication theory, wireless radios have undergone a significant revolution. Currently many approaches have been proposed to increase capacity and flexibility of wireless systems. Typical examples include directional and smart antennas [117,124], MIMO systems [139,126], and multi-radio/multi-channel systems [122,3]. To date, MIMO has become one of the key technologies for IEEE 802.11n [64], the high speed extension of Wi-Fi. Multi-radio chipsets and their development platforms are available on the market [44].
  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 [97,89], and even software radios [102] have been used in 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 capability of dynamically controlling the radios. These advanced wireless radio technologies all require a revolutionary design in higher layer protocols, especially MAC and routing protocols. For example, when directional antennas are applied to IEEE 802.11 networks, a routing protocol needs to take into account the selection of directional antenna sectors. Directional antennas can reduce exposed nodes, but they also generate more hidden nodes. Thus, MAC protocols need to be re-designed to resolve this issue. As for MIMO systems, new MAC protocols are also necessary [126]. When software radios are considered, much more powerful MAC protocols, such as programmable MAC, need to be developed.
- *Scalability*. Multi-hop communication is common in WMNs. For multi-hop networking, it is well known that communication protocols suffer from scalability issues [62,72], i.e., when the size of network increases, the network performance degrades significantly. 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. As a typical example, current IEEE 802.11 MAC protocol and its derivatives cannot achieve a reasonable throughput as the number of hops increases to 4 or higher (for 802.11b, the TCP throughput

is lower than 1.0 Mbps). The reason for low scalability is that the end-to-end reliability sharply drops as the scale of the network increases. In WMNs, due to its ad hoc architecture, the centralized multiple access schemes such as TDMA and CDMA are difficult to implement due to their complexities and a general requirement on timing synchronization for TDMA (and code management for CDMA). When a distributed multi-hop network is considered, accurate timing synchronization within the global network is difficult to achieve [62]. Thus, distributed multiple access schemes such as CSMA/CA are more favorable. However, CSMA/CA has very low frequency spatial-reuse efficiency [2], which significantly limits the scalability of CSMA/CA-based multi-hop networks. To improve the scalability of WMNs, designing a hybrid multiple access scheme with CSMA/CA and TDMA or CDMA is an interesting and challenging research issue.

- *Mesh connectivity*. Many advantages of WMNs originate from mesh connectivity which is a critical requirement on protocol design, especially for MAC and routing protocols. Network self-organization and topology control algorithms are generally needed. Topology-aware MAC and routing protocols can significantly improve the performance of WMNs.
- *Broadband and QoS*. Different from other ad hoc networks, most applications of WMNs are broadband services with various 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.
- *Compatibility and inter-operability*. It is a desired feature for WMNs to support network access for both conventional and mesh clients. Thus, WMNs need to be backward compatible with conventional client nodes; otherwise, the motivation of deploying WMNs will be significantly compromised. Integration of WMNs with other wireless networks requires certain mesh routers to have the capability of inter-operation among heterogeneous wireless networks.
- *Security*. Without a convincing security solution, WMNs will not be able to succeed due to lack of incentives by customers to subscribe to reliable services. Although many security schemes have been proposed for wireless LANs, they are still not ready 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, but several issues exist:
  - Most security solutions for ad hoc networks are still not mature enough to be practically implemented.
  - The network architecture of WMNs is different from a conventional ad hoc network, which causes differences in security mechanisms.

  As a consequence, new security schemes ranging from encryption algorithms to security key distribution, secure MAC and routing protocols, intrusion detection, and security monitoring need to be developed.
- *Ease of use*. Protocols must be designed to enable the network to be as autonomous as possible, in the sense of power management, self-organization, dynamic topology control, robust to temporary link failure, and fast network-subscription/user-authentication procedure. 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 protocols will enable rapid deployment of WMNs.

6. Capacity of WMNs

The capacity of WMNs is affected by many factors such as network architecture, network topology, traffic pattern, network node density, number of channels used for each node, transmission power level, and node mobility. A clear understanding of the relationship between network capacity and the above factors provides

a guideline for protocol development, architecture design, deployment and operation of the network.

6.1. Capacity analysis

In the last decade, much research has been carried out to study the capacity of ad hoc networks which can be adopted to investigate the capacity of WMNs.

For a stationary multi-hop network, it has been shown that the optimum transmission power level of a node is reached when the node has six neighboring nodes [81]. With this value, an optimum tradeoff is achieved between the number of hops from source to destination and the channel spatial-reuse efficiency. This result is useful for infrastructure WMNs with minimal mobility. When the mobility is a concern as in hybrid WMNs, no theoretical results are reported so far. Some experimental studies have been performed in [16], where the simulation results of a stationary network validate the theoretical results of [81].

Analytical lower and upper bounds of network capacity are given in [54]. From the analytical results, it follows that the throughput capacity per node reduces significantly when the node density increases. An important implication is derived in [54] as a 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 [54]:

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

Thus, communications of a node with another node that is not nearby must be conducted through relaying nodes or clusters. However, these schemes have limitations. In the first scheme, a very large number of relaying nodes are needed in order to increase the throughput by a significant percent. This will definitely increase the overall cost of a network. In the second scheme, clustering nodes in ad hoc networks or WMNs is not a preferred approach, because it is difficult to manage clusters in a distributed system.

Nevertheless, this implication has motivated other research work such as [83,93], where a hybrid network architecture is considered to improve the capacity of ad hoc networks. In the hybrid architecture, nodes only communicate with nearby nodes. If they need to communicate with nodes with many hops away, base stations or access points are used to relay packets via wired networks. The hybrid architecture can improve capacity of ad hoc networks, however, it may still not be favored by many applications because wired connections between base stations do not exist in many ad hoc networks.

The implication given in [54] can also be reflected in [130]. The scheme proposed in [130] increases the network capacity of ad hoc networks by utilizing the node mobility. When a node needs to send packets to another node, it will not send until the destination node is close to the source node. Thus, via the node mobility, a node only communicates with its nearby nodes. This scheme has a limitation: The transmission delay may become large and the required buffer for a node may be infinite.

The analytical approach in [54] has significantly driven the progress in capacity research of ad hoc networks. However, it contains limitations. The networking protocols have not been fully captured by the analysis. For example, power control mechanisms, commonly used to improve the network capacity, is not considered in the analysis. As another example, the characteristics of ad hoc routing protocols have not been totally captured in the analysis. In any routing protocol, the route for packets does not necessary follow the path along the straight-line segment between the source and destination as given in the analysis, because the routing protocol determines a path according to certain metrics such as the number of hop counts, link quality, etc. [41].

As a result, the applicability of the theoretical results on practical network architectures still remains unclear. A close match between the theoretical results in [54] and IEEE 802.11 based ad hoc networks is reported in [90]. However, this study relies on the assumption that the traffic pattern in a large ad hoc network tends to be local and thus, nodes usually communicate with nearby

nodes. This assumption is not always valid in a network unless it is intentionally designed so.

Most of the existing analytical approaches are based on asymptotic analysis [54]. The upper or lower capacity bounds derived from these approaches do not reveal the exact capacity of an ad hoc network with a given number of nodes, in particular when the number is small. Recently, an analytical approach is proposed in [75] to study the exact capacity of WMNs. The analysis is simplified by taking advantage of the low mobility feature of WMNs. However, the analytical model in [75] contains three assumptions that are not necessarily valid.

- The traffic in all nodes is sent to a single gateway which is not the case in WMNs.
- Each node receives an equal share of the bandwidth to achieve fairness. However, this assumption is not valid if the network nodes have different distances between them.
- The unidirectional traffic case is mentioned to be easily extendable to the bidirectional traffic case. However, the network capacity becomes totally different if bidirectional traffic is considered.
- The network architecture considered is actually still an ad hoc network. Furthermore, only a specific MAC protocol very similar to CSMA/CA with RTS/CTS is considered. However, CSMA/CA is not the only MAC solution for mesh networks. For example, the IEEE 802.11e or a TDMA MAC can achieve higher throughput than CSMA/CA, because of the existence of contention free periods (CFP).

6.2. Open research issues

Many research issues still exist in the capacity analysis of WMNs for several reasons:

1. The theoretical results on the capacity of either ad hoc networks or WMNs are still based on some simplified assumptions, as explained before. The derivation of new results by considering critical factors such as transmission power levels, traffic patterns, optimal routing path, etc., is still a challenging research topic.
2. Despite much research progress has been made in network capacity analysis of ad hoc networks, WMNs have not been fully explored due to the differences between WMNs and ad hoc networks. The research results about network capacity and optimum node density of ad hoc networks may not directly be applicable to WMNs. For example, in [54], the network architecture in the analysis does not match that of WMNs, because both stationary and mobile ad hoc nodes exist in WMNs.
3. Important techniques of increasing capacity of WMNs have not been considered in the analytical models for ad hoc networks. For example, multi-channels per radio or multi-radios per node will be applied in WMNs. Then, a critical question that arises is: what is the optimum number of channels or radios for each network node. Although the analytical model in [54] allows multi-channels in a node, it does not contain a scheme to find the optimum number of channels. When other advanced techniques such as directional antennas, multi-input multi-output (MIMO) systems, are considered, new analytical models are required.

7. Physical layer

7.1. Advanced physical layer techniques

Physical layer techniques advance fast as RF and circuit design for wireless communications evolve. Most of existing wireless radios are able to support multiple transmission rates by a combination of different modulation and coding rates [67,68]. With such modes, adaptive error resilience can be provided through link adaptation [115,31,52]. It should be noted that under a frequency selective fading environment, a link adaptation algorithm cannot take signal-to-noise ratio (SNR) or carrier-to-interference ratio (CIR) as a single input from the physical layer, because SNR or CIR alone does not adequately describe the channel quality [88].

In order to increase the capacity of wireless networks, various high-speed physical techniques have been invented. For example, orthogonal

frequency multiple access (OFDM) has significantly increased the speed of IEEE 802.11 from 11 Mbps to 54 Mbps. A much higher transmission rate can be achieved through ultra-wide band (UWB) techniques. However, UWB is only applicable to short-distance applications such as wireless personal area networks (WPANs). If a transmission speed as high as that of UWB is desired in a wider area network such as WLANs or WMANs, new physical layer techniques are needed.

In order to further increase capacity and mitigate the impairment by fading, delay-spread, and co-channel interference, multiple-antenna systems have been used for wireless communication [104,21]. Considering communications between nodes A and B in Fig. 12, node A is assumed to have M antennas for transmission and N antennas for reception, while in node B there are K antennas for transmission and L antennas for reception. Different values of M, N, K, L result in various multiple-antenna systems. If multiple antennas are in the receiver but single channel in the transmitter (i.e., $K = 1$, $M = 1$ and either $L > 1$ or $N > 1$), techniques such as antenna diversity and adaptive/smart antennas can be used for a multi-antenna system. They have been proposed for point-to-multipoint one-hop cellular networks. Antenna diversity is based on the fact that signals received from uncorrelated antennas have independent fading. Thus, it has high probability that at least one good signal can be received at the receiver. Antenna uncorrelation is usually achieved through space, polarization, or pattern diversity, and the processing technologies for diversity include switch diversity, equal gain, and maximum ratio combining [104]. When strong interference is present, diversity processing alone is insufficient to receive signals with high quality. To resolve this issue, adaptive antenna array processing is used to shape the antenna beamform so as to enhance the desired signals while to nullify the interfering signals. The technique for adaptive antenna processing is called optimum combining. It assumes that part information of the desired signal can be acquired through a training sequence.

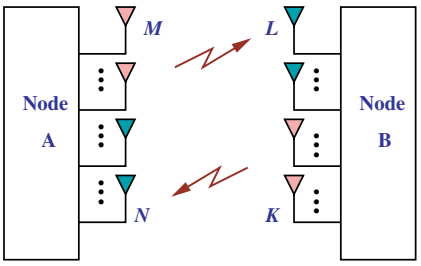

Fig. 12. Multiple-antenna systems.

Antenna diversity and smart antenna techniques are also applicable to WMNs and other ad hoc networks. However, their performance in WMNs or any other ad hoc networks needs more evaluation. Examples of analyzing smart antenna systems for MANETs are reported in [18,117]. Due to complexity and cost, a fully adaptive smart antenna system is only used in base stations of cellular networks. On-going research and development efforts are still needed to implement fully adaptive smart antenna system in a mobile terminal. For WMNs, low-cost is a challenging issue. As a consequence, directional antennas have been actively researched in the area of ad hoc networks. A mechanically or electronically steerable or switched directional antenna system can be tuned to a certain direction. By using directional transmission, interference between network nodes can be mitigated and thus, network capacity can be improved [124,118]. Directional antenna can also improve energy efficiency [123]. However, directional antennas bring challenges to the MAC protocol design [144,105,82,36].

If multiple antennas are in the transmitter and single antenna in the receiver, i.e., $N = 1$, $L = 1$ and either $K > 1$ or $M > 1$, antenna diversity or smart antenna cannot be applied unless the channel state information (CSI) is available. However, usually partial information of channel state is available at the transmitter. To achieve diversity under this situation, a commonly used technique is space–time coding (STC) [12], where signals transmitted at different antennas in different symbol periods are processed with a certain coding technique. The received signals are then combined at the receiver through an appropriate algorithm such as maximum likelihood detection (MLD). STC is a promising technique that achieves second order diversity without bandwidth expansion

[104]. To date, if CSI is not available, no solution has been developed yet for smart antennas at a transmitter. Schemes such as [35] still assume that CSI is perfectly known.

If multiple antennas are in both the transmitter and the receiver, i.e., $M > 1$, $L > 1$ or $K > 1$, $N > 1$, the multiple-antenna system is an MIMO system, where both diversity and simultaneous transmissions exist. Thus, MIMO can potentially increase the system capacity by three times or even more [94]. Currently MIMO is being adopted into IEEE 802.11n [64]. Depending on where the MIMO processing is placed, MIMO systems can be categorized into three types: receiver processing only, transmitter processing only, and both transmitter and receiver processing MIMO systems. The processing techniques can be based on maximum likelihood detection (MLD), vertical Bell Lab Layered Space–Time (V-BLAST) [51], singular value decomposition (SVD) [13], and space–time coding. So far only few results have been reported on the research of applying STC and MIMO to WMNs as well as other ad hoc networks.

Since multiple channels are usually available in the frequency band of a wireless radio, they can be used to increase the capacity. A single-transceiver radio can use different channels by channel switching on the time axis according to the needs of higher layer protocols. For a multi-transceiver radio, simultaneous transmissions in different channels can be supported. Multiple transceivers can be easily implemented in a base station of cellular networks. However, with the concern of cost and system complexity, a wireless radio with multiple transceivers has not become a mature technique yet, although IEEE 802.11 chipsets with multiple transceivers are already available [44]. In some situations, the system capacity of a network node can be improved by using multiple radios each with single or multiple channels. Since each radio contains both MAC and physical layers, in order to make a multi-radio network work as a single node, a virtual MAC protocol is usually required to coordinate the communication in all radios [3].

For a wireless network, the frequency band is a very precious resource. However, many of existing allocated frequency bands (both licensed and unlicensed) have not been utilized efficiently. Measurements by the FCC show that around 70% of allocated spectrum is not utilized [45,89]. In addition, the time scale of spectrum occupancy can vary from milliseconds to hours [45]. Therefore, abundant spectrum is still available for wireless communication. Furthermore, in a large scale ad hoc network, the complexity is beyond human planning, and thus, conventional static frequency planning becomes impossible [96]. To achieve much better spectrum utilization and viable frequency planning, frequency agile [97] or cognitive radios [89] are being developed to dynamically capture this unoccupied spectrum. The FCC has recognized the promising future of this technique and pushes to enable it to a full realization. In order to implement cognitive radios, software defined radio (SDR) is one of the most convenient platforms [46] because programmability exists in all components of a radio such as programmable RF bands, channel access modes, and channel modulations [102]. SDR is not a mature technique yet, although testbeds are available now [139]. However, for the long term, SDR will be a key technique for wireless communications. It cannot only realize the cognitive radios, but can also easily implement all other advanced physical techniques such as adaptive modulation and coding, MIMO system [139], controller for smart and directional antennas, multi-channel radio, and multi-radio systems.

7.2. Open research issues

Open issues in the physical layer are twofold. First, 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 WMNs. An example of low-cost directional antenna implementation is reported in [76]. Frequency agile techniques are still in the early phase. Many challenging issues need to be resolved before they can be accepted for commercial use [89].

Second, to best utilize the advanced features provided by physical layer, higher layer protocols, especially MAC protocols, need to be carefully designed. Otherwise, the advantages brought by such physical layer techniques will be significantly compromised. For directional and smart antennas, many MAC protocols have been proposed for ad hoc networks [144,105,82,36]. A MAC protocol for MIMO systems is studied in [126]. However, for multi-antenna systems, an efficient MAC protocol to achieve significant throughput improvement is still needed, as will be discussed in Section 8. Communication protocols for cognitive radios remain an open issue. Significant research efforts are needed to make cognitive-radio based WMNs become practical.

8. MAC layer

MAC protocols for WMNs have the following differences compared to classical counterparts for wireless networks:

- *MAC for WMNs is concerned with more than one hop communication.* Classical MAC protocols are limited to one-hop communication while the routing protocol takes care of multi-hop communication. This assumption makes protocol design easier, since MAC and routing are transparent to each other. However, this method does not work well in WMNs, because data transmission and reception at a node is not only affected by nodes within one hop but within two or more hops away. The hidden-node issue in a multi-hop wireless LAN is such an example.
- *MAC is distributed and cooperative and works for multipoint-to-multipoint communication*. In WMNs, no centralized controller is available. The MAC function is accomplished in a distributed way, i.e., the MAC protocol must ensure all nodes to cooperate in transmission. In addition, any network node with mesh networking capability is able to communicate all its neighboring mesh nodes. Thus, multipoint-to-multipoint communications can be established among these nodes.
- *Network self-organization is needed for the MAC*. MAC protocol should have the knowledge about network topology which can help better cooperation between neighboring nodes and nodes in multi-hop distances. This can significantly improve the MAC performance in a multi-hop environment. In some circumstances, network self-organization based on power control can optimize network topology [91], minimize the interference between neighboring nodes, and thus, improve the network capacity.
- *Mobility affects the performance of MAC.* Mobility dynamically changes network configuration, and thus, may significantly impact the performance of the MAC protocol. In order to be adaptive to mobility or even to utilize the mobility [130], the network nodes need to exchange network topology information.

These differences must be considered in order to design a scalable MAC for WMNs.

The scalability of WMNs can be addressed by the MAC layer in two ways. The first way is to enhance existing MAC protocols or propose new MAC protocols to increase end-to-end throughput when only single channel is available in a network node. The second way is to allow transmission on multiple channels in each network node. In the following, existing single-channel and multi-channel MAC protocols are studied separately. Since IEEE 802.11 is a widely accepted radio technique for WMNs, most of the following discussions are focused on the IEEE 802.11 MAC, i.e., CSMA/CA with RTS/CTS.

8.1. Single-channel MAC

There are three approaches in this case:

- *Improving existing MAC protocols*. Currently several MAC protocols have been proposed for multi-hop ad hoc networks by enhancing the CSMA/CA protocol [27,116]. These schemes usually adjust parameters of CSMA/CA such as contention window size and modify backoff procedures. They may improve throughput for

one-hop communications. However, for multi-hop cases such as in WMNs, these solutions still reach a low end-to-end throughput, because they cannot significantly reduce the probability of contentions among neighboring nodes. As long as contention occurs frequently, whichever method is taken to modify backoff and contention resolution procedures, the end-to-end throughput will be significantly reduced due to the accumulating effect on the multi-hop path.

- *Cross-layer design with advanced physical layer techniques.* Two major schemes exist in this category: MAC based on directional antenna [82,36] and MAC with power control [112]. The first set of schemes eliminates exposed nodes if antenna beam is assumed to be perfect. However, due to the directional transmission, more hidden nodes are produced in this case. Thus, new solutions must be developed to reduce the number of hidden nodes. Moreover, MAC protocols based on directional antennas also face other difficulties such as cost, system complexity, and practicality of fast steerable directional antennas. The second set of schemes is developed for the purpose of reducing power consumptions [33,147,131]. These schemes reduce exposed nodes problem, especially in a dense network, and thus, improve the spectrum spatial-reuse factor in WMNs [2]. However, hidden nodes still exist and may become worse because lower transmission power level reduces the possibility of detecting a potential interfering node [72].
- *Proposing innovative MAC protocols*. In order to fundamentally resolve the issue of low end-to-end throughput in a multi-hop ad hoc environment such as WMNs, innovative solutions are necessary. Determined by their poor scalability in an ad hoc 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 an important research topic [78,134]. To date, few TDMA or CDMA MAC protocols have been proposed for WMNs. This is 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. A distributed TDMA MAC for IEEE 802.16 mesh is still being researched. In WMNs based on IEEE 802.11, how to design a distributed TDMA MAC protocol overlaying CSMA/CA is an interesting but challenging problem [134]. For distributed TDMA or CDMA MAC protocols, network self-organization based on topology control and/or power control must also be considered.

8.2. Multi-channel MAC

A multi-channel MAC can be implemented on several different hardware platforms, which also impacts the design of the MAC. A multi-channel MAC may belong to one of the following categories:

- *Multi-channel single-transceiver MAC*. If the 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 in order to improve system capacity. To coordinate transmissions between network nodes under this situation, protocols such as the multi-channel MAC in [122] and the seed-slotted channel hopping (SSCH) scheme [14] are needed. SSCH is actually a virtual MAC protocol, since it works on top of IEEE 802.11 MAC and does not need changes in the IEEE 802.11 MAC.
- *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, there is only one MAC layer to coordinate the functions of multiple channels. Engim multi-channel wireless LAN switching engine [44] belongs to this category. However, how to design an efficient MAC

protocol for this type of physical layer platform is still an open research topic.
- *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) [3] is required on top of MAC to coordinate communications in all channels. In fact one radio can have multiple channels. However, for simplicity of design and application, a single channel is used in each radio.

To illustrate typical issues existing in multi-channel MAC protocols, here we explain two protocols in detail: *multi-channel MAC* (MMAC) [122] and *multi-radio unification protocol* (MUP) [3].

As far as MMAC is concerned, there are three main functions:

- *Maintaining data structure of all channels in each node*. Channels of a node are classified into three types depending on its status of allocation.
- *Negotiating channels during ad hoc traffic indication message (ATIM) window*. Negotiations are done through a pre-defined channel known to all nodes.
- *Selecting a channel*. The criterion is to use a channel with the lowest count of source–destination pairs that have selected the channel.

Several problems have not been solved in the MMAC [122].

- It is assumed that RTS/CTS always work in IEEE 802.11 DCF. In reality, RTS/CTS is an optional function of DCF, and it may cause a high standard.
- Global synchronization in the network is difficult to achieve in an ad hoc network with a large number of hops and nodes.
- The channel switching time may be much larger than 224 μs [122]. A larger channel switching time will significantly degrade the performance of a multi-channel MAC protocol [3].
- Channel selection criterion based on the lowest number of source–destination pairs for each channel is not always appropriate. Using pending packets as a metric to select a channel achieve better performance [122].
- The MMAC eliminates multi-channel hidden nodes, but it also generates many exposed nodes because of using RTS/CTS and ATIM/ATIM-ACK (for default channel) procedures.

In MUP, there are multiple wireless network interface cards (NICs) on each node. Channels on all NICs are orthogonal and fixed. The major functions of MUP [3] include:

- *Discovering neighbors*. After the discovering procedures, neighbors are classified into MUP-enabled and legacy nodes.
- *Selecting a NIC based on one-hop round trip time (RTT) measurements*. MUP selects the NIC with the shortest RTT between a node and its neighbors.
- *Utilizing the selected NIC for a long period*. This period is determined by a random process and in the order of 10–20 s.
- *Switching channels*. After the random time period, all NICs are measured again through one-hop probe messages. If an NIC has a certain amount of quality improvement than the existing NIC, then it is selected for sending packets.

Several issues still need to be investigated further:

- *Hidden node issue is not effectively solved.* The channel quality measurement is based on one-hop RTT. However, measurements based on shortest RTT do not guarantee that there exists no hidden nodes. For example, suppose nodes A and C are hidden from each other and node B is a neighbor of both A and C. Then the same channel can be selected by nodes A and C. The RTS/CTS mechanism can be applied to reduce the collision probability in this situation, but it causes very high overhead.
- *NIC switching mechanism is not justified.* MUP allocates a random time period for each selected NIC. Performance of this scheme cannot be guaranteed, because the time of having the best

quality in a NIC is not randomized but related to the wireless channel characteristics and interference from nodes using the same channel.
- *Packet re-ordering is needed after NIC switching.* MUP relies on TCP to handle this issue. However, this will cause low end-to-end throughput in a multi-hop network like WMNs.

In addition, fixed channel assignment on each NIC also limits the flexibility of MUP.

8.3. Open research issues

To the best of our knowledge, the scalability issue in multi-hop ad hoc networks has not been fully solved yet. Most of existing MAC protocols based on CSMA/CA solve partial problems of the overall issue, but raise other problems. Thus, how to fundamentally improve the scalability of CSMA/CA is a challenging problem. A distributed TDMA MAC overlaying CSMA/CA [134] addressed one possible solution to this problem. For networks based on techniques other than CSMA/CA, both TDMA and CDMA can be applied to WMNs, if a distributed scheme can be developed to locally eliminate the difficulties of implementing TDMA or CDMA in an ad hoc network. Many other interesting research problems related to the scalability issue of ad hoc networks still remain to be solved. When advanced techniques such as MIMO and cognitive radios are used in the physical layer, novel MAC protocols need to be proposed to utilize the agility provided by the physical layer.

Due to the differences between WMNs and ad hoc networks, a scalable MAC protocol for ad hoc networks may not be effective to WMNs. In WMNs, mesh routers and mesh clients hold significantly different characteristics such as mobility, power constraints, etc. Same distributed solution may not work for both mesh routers and clients. Thus, a MAC protocol for WMNs must consider both scalability and heterogeneity between different network nodes.

Some mesh routers in WMNs are responsible for 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.

Multi-channel MAC protocols for radios with multiple transceivers have not been thoroughly explored, possibly due to the relatively high cost of such radios. However, as the cost goes down, a multi-channel multi-transceiver MAC will be a rather promising solution for WMNs. To really achieve spectrum efficiency, a multi-channel MAC protocol must include the single-channel solution that can fundamentally resolve the scalability issue of WMNs. Otherwise, the throughput per node per channel will still be very low. How to apply the innovative single-channel solution to a multi-radio or multi-channel system is another research problem.

Most of the existing research efforts in MAC are focused on capacity, throughput, and fairness. However, many applications need to support broadband multimedia communication in WMNs. Thus, the development of MAC protocols with multiple QoS metrics such as delay, packet loss ratios, and delay jitter is an important topic for WMNs.

Another challenge related to MAC is the implementation, because both software and firmware may be involved when a MAC protocol is to be modified. As an example in IEEE 802.11 MAC, although chipset manufacturers have put efforts to pull up more functions in the firmware into the driver level as software, many timing critical functions remain in the firmware. Such a "thin" MAC solution provides little flexibility in modifying MAC protocols. To avoid modifying firmware, one approach is to design a MAC without coupling with firmware. For example, the virtual MAC protocols do not require any modification in firmware or hardware. However, in some circumstances key functions in the firmware need to be modified in order to significantly improve the performance of the MAC protocol. Changing the firmware is a doable but not a viable solution due to its cost and complexity. A solution to this problem is to choose a more flexible MAC protocol architecture. To our knowledge, there are sev-

eral IEEE 802.11 chipset manufacturers that have eliminated firmware in their MAC implementation architecture. With such an architecture, a true soft MAC [134] or even a programmable MAC can be implemented. When software radios become mature enough for commercial use, more flexible and powerful MAC protocols can be easily developed.

9. Network layer

WMNs will be tightly integrated with the Internet, and IP has been accepted as a network layer protocol for many wireless networks including WMNs. However, routing protocols for WMNs are different from those in wired networks and cellular networks. Therefore, we focus our study on routing protocols in this section.

Since WMNs share common features with ad hoc networks, the routing protocols developed for ad hoc networks can be applied to WMNs. For example, mesh routers of Firetide Networks [47] are based on topology broadcast based on reverse-path forwarding (TBRPF) protocol [108], Microsoft mesh networks [101] are built based on dynamic source routing (DSR) [73], and many other companies [80] are using ad hoc on-demand distance vector (AODV) routing [109].

Despite the availability of several routing protocols for ad hoc networks, the design of routing protocols for WMNs is still an active research area for several reasons. First of all, new performance metrics need to be discovered and utilized to improve the performance of routing protocols. In addition, existing routing protocols still have limited scalability. Moreover, the existing routing protocols treat the underlying MAC protocol as a transparent layer. However, the cross-layer interaction must be considered to improve the performance of the routing protocols in WMNs. More importantly, the requirements on power efficiency and mobility are much different between WMNs and ad hoc networks. In a WMN, nodes (mesh routers) in the backbone have minimal mobility and no constraint on power consumption, while mesh client nodes usually desire the support of mobility and a power efficient routing protocol. Such differences imply that the routing protocols designed for ad hoc networks may not be appropriate for WMNs.

Based on the performance of the existing routing protocols for ad hoc networks and the specific requirements of WMNs, we believe that an optimal routing protocol for WMNs must capture the following features:

- *Performance metrics*. Many existing routing protocols use minimum hop-count as a performance metric to select the routing path. This has been demonstrated not to be valid in many situations. Suppose a link on the minimum hop-count path between two nodes has bad quality. If the minimum hop count is used as the performance metric, then the throughput between these two nodes will be very low. To solve this problem, performance metrics related to link quality are needed. If congestion occurs, then the minimum-hop count will not be an accurate performance metric either. Usually Round trip time (RTT) is used as an additional performance metric. The bottomline is that a routing path must be selected by considering multiple performance metrics.
- *Fault tolerance with link failures*. One of the objectives to deploy WMNs is to ensure robustness in link failures. If a link breaks, the routing protocol should be able to quickly select another path to avoid service disruption.
- *Load balancing*. One of the objectives of WMNs is to share the network resources among many users. When a part of a WMN experiences congestion, new traffic flows should not be routed through that part. Performance metrics such as RTT help to achieve load balancing, but are not always effective, because RTT may be impacted by link quality.
- *Scalability*. Setting up a routing path in a very large wireless network may take a long time, and the end-to-end delay can become large. Furthermore, even when the path is established, the node states on the path may change. Thus, the scalability of a routing protocol is critical in WMNs.
- *Adaptive Support of Both Mesh Routers and Clients.* Considering the minimal mobility and no

constraint of power consumption in mesh routers, a much simpler routing protocol can be developed for mesh routers than existing ad hoc routing protocols. However, for mesh clients, the routing protocol must have the full functions of ad hoc routing protocols. Consequently, it is necessary to design an efficient routing protocol for WMNs that can adaptively support both mesh routers and mesh clients.

In the rest of this section, we discuss various routing protocols applicable to WMNs and emphasize the open research issues.

9.1. Routing protocols with various performance metrics

The impact of performance metrics on a routing protocol is studied in [41], where the link quality source routing (LQSR) is proposed on the basis of DSR. LQSR aims to select a routing path according to link quality metrics. Three performance metrics, i.e., the expected transmission count (ETX) [39], per-hop RTT, and per-hop packet pair are implemented separately in LQSR.

The performance of the routing protocol with these three performance metrics is also 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. The reason is that, as the sender moves, the ETX metric cannot quickly track the change in the link quality. This result illustrates that the link quality metrics used in [41] are still not enough for WMNs when mobility is concerned. Better performance metrics need to be developed, and routing protocols integrating multiple performance metrics are necessary for WMNs.

9.2. Multi-radio routing

In WMNs, multi-radio per node may be a preferred architecture, because the capacity can be increased without modifying the MAC protocol. A routing protocol is proposed in [42] for multi-radio WMNs. A new performance metric, called the weighted cumulative expected transmission time (WCETT) is proposed for the routing protocol. WCETT takes into account both link quality metric and the minimum hop-count. It can achieve good tradeoff between delay and throughput because it considers channels with good quality and channel diversity in the same routing protocol.

In WMNs, multi-channel per radio is another alternative to improve the capacity. For this type of networks, the scheme proposed in [42] is not applicable because significant differences exist between a multi-channel node and a multi-radio node as explained in Section 8.

9.3. Multi-path routing for load balancing and fault tolerance

The main objective of using multi-path routing is to perform better load balancing and to provide high fault tolerance [103]. Multiple paths are selected between source and destination. Packets flow in one of these selected paths. When 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 for setting up a new routing path, the end-to-end delay, throughput, and fault tolerance can be improved. However, the improvement depends on the availability of node-disjoint routes between source and destination.

A drawback of multi-path routing is its complexity. Whether or not the multi-path routing can be used for WMNs needs to be investigated depending on applications. Another problem is that multi-path routing is infeasible if the shortest path is taken as the routing performance metric. Unless a large number of shortest paths are selected, load distribution is almost the same as single shortest path routing [50]. Thus, how to design an effective multi-path routing protocol with appropriate performance metrics is an interesting research topic.

9.4. Hierarchical routing

Numerous hierarchical routing protocols [17,120,140] have been proposed in recent years. In-

stead of addressing each of them, we describe the common principle of these routing protocols.

In hierarchical routing, 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 are needed, some nodes can communicate with more than one cluster and work as a gateway. Routing within a cluster and routing between clusters may use different mechanisms. For example, inter-cluster routing can be a proactive protocol, while intra-cluster routing can be on demand [120].

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. In WMNs, hierarchical routing actually may face the implementation difficulty, because a node selected as a cluster head may not necessarily have higher processing capability and channel capacity than the other nodes. Unless being intentionally designed so, the cluster head may become a bottleneck. Hierarchical routing provides a possible approach for scalability. However, whether or not these hierarchical schemes can really solve the scalability problem still remains a question.

9.5. 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 [48]. Thus, topology change has less impact on the geographic routing than other routing protocols.

Early geographic routing algorithms are actually a type of single-path greedy routing schemes in which packet forwarding decision is made based on the location information of current forwarding node, its neighbors, and the destination node. Various greedy routing algorithms differ in the optimization criterion applied in the forwarding decision. To improve power efficiency, a greedy algorithm is proposed in [58], which reduces signaling overhead by eliminating the periodic *hello* messages in other greedy routing algorithms. However, all greedy routing algorithms have a common problem: *Delivery is not guaranteed even if a path exists between source and destination*. Partial flooding and keeping the past routing information can help to guarantee delivery. However, these approaches increase communication overhead and lose the stateless property of single-path greedy routing [48].

In order to keep the stateless property and guarantee delivery, planar-graph based geographic routing algorithms are proposed recently [23,38]. However, open issues still remain in these algorithms. For example, in the face routing algorithm [23], the communication overhead is much higher than in the single-path greedy routing algorithm [48]. Thus, the face routing algorithm is mainly used as a recovery scheme when the greedy routing algorithm fails.

9.6. Open research issues

Scalability is the most critical question in WMNs. 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. Moreover, the inquiry of destination position produces additional traffic load. Thus, new scalable routing protocols need to be developed. Existing performance metrics incorporated into routing protocols need to be expanded. Moreover, how to integrate multiple performance metrics into a routing protocol so that the optimal overall performance is achieved is a challenging issue.

Routing for multicast applications is another important research topic. Many applications of WMNs need multicasting capability. For example, in a community or a city-wide network, video distribution is a common application.

Cross-layer design between routing and MAC protocols is another interesting research topic. Previously, routing protocol research was focused on layer-3 functionality only. However, it has been shown that the performance of a routing protocol

may not be satisfactory in this case. Adopting multiple performance metrics from layer-2 into routing protocols is an example. However, interaction between MAC and routing is so close that merely exchanging parameters between protocol layers is not adequate. Merging certain functions of MAC and routing is a promising approach.

When multi-radio or multi-channel wireless mesh nodes are considered, new routing protocols are needed for two reasons. First, the routing protocol not only needs to select a path in-between different nodes, it also needs to select the most appropriate channel or radio on the path. Second, cross-layer design becomes a necessity because change of a routing path involves the channel or radio switching in a mesh node. Without considering cross-layer design, the switching process may be too slow to degrade the performance of WMNs.

The existing routing protocols treat all network nodes in the same way. However, such solutions may not be efficient for WMNs, because the mesh routers in WMNs backbone and mesh clients have significant differences in power constraint and mobility. More efficient routing protocols that take into account these differences are desired for WMNs.

10. Transport layer

To the best of our knowledge, no transport protocol has been introduced specifically for WMNs to date, although several transport protocols have been developed for both wired and wireless networks in the last decade. In this section, we explain existing transport protocols with a focus on ad hoc networks, since WMNs share common features with ad hoc networks in spite of their differences. Then, we also discuss the research challenges.

10.1. Protocols for reliable data transport

To date, a large number of reliable transport protocols have been proposed for ad hoc networks. They can be classified into two types: TCP variants and entirely new transport protocols. TCP variants [15,29,59,92] include transport protocols that are an enhanced version of the classical TCP for wired networks. In an entirely new transport protocol [127], the reliable transport mechanism is designed from a fresh start, with an objective to avoid fundamental problems in TCP.

10.1.1. TCP variants

The performance of classical TCPs degrades significantly in ad hoc networks. In this section, we discuss various enhanced TCP protocols by addressing the fundamental problems in TCP and the corresponding solutions.

One of the well-known reasons for TCP performance degradation is that the classical TCPs do not differentiate congestion and non-congestion losses [142]. As a result, when non-congestion losses occur, the network throughput quickly drops. Moreover, once wireless channels are back to the normal operation, the classical TCP cannot be recovered quickly. The protocol in [29] enhances TCP through a feedback mechanism to differentiate between losses caused by congestion or wireless channels. This concept can be adopted to WMNs. However, how to design a loss differentiation approach and accordingly modify the TCP for WMNs accordingly is subject to future study.

Link failure also degrades the TCP performance. Link failure may occur 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, congestion losses and link failure also need to be differentiated. Schemes similar to explicit link failure notification (ELFN) scheme [59] can perform such differentiations.

TCP is critically dependent on ACK, so its performance can be severely impacted by network asymmetry which is defined as the situation where the forward direction of a network is significantly different from the reverse direction in terms of bandwidth, loss rate, and latency [15]. In WMNs, TCP data and TCP ACK packets may take different paths, and thus experience different packet loss

rate, latency, or bandwidth. Even if the same path is taken by TCP data and ACK packets, they still face network asymmetry problem, because the channel condition and bandwidth on the path varies from time to time. Consequently, TCP has poor performance for wireless multihop ad hoc networks [110,141]. To solve the network asymmetry problem, schemes such as ACK filtering, ACK congestion control, etc., [15] have been proposed. However, a different network architecture is studied in [15], i.e., the effectiveness of these schemes in WMNs needs investigation.

In WMNs, mesh routers and mesh clients are connected as an ad hoc network, so dynamic change of routing path is common. Considering mobility, variable link quality, traffic load, and other factors, the change may be frequent and may cause large variations in RTT. This will degrade the TCP performance, because the normal operation of TCP relies on a smooth measurement of RTT [1]. How to enhance a TCP so that it is robust to large RTT variations has not been thoroughly studied for both mobile ad hoc networks and WMNs.

10.1.2. Entirely new transport protocols

As discussed before, many fundamental problems exist in TCP. Therefore, some researchers have started to develop entirely new transport protocols for ad hoc networks.

In [127], 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. The 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. By using an entirely new set of mechanisms for reliable data transport, ATP achieves much better performance (e.g., delay, throughput, and fairness) than the TCP variants.

Despite its advantages, an entirely new transport protocol is not favored by WMNs due to the compatibility issue. ATP [127] assumes that the wireless network can be stand-alone. While this may be true for mobile ad hoc networks, it is invalid for WMNs, since WMNs will be integrated with the Internet and many other wireless networks. Transport protocols for WMNs must be compatible with TCPs in other networks.

10.2. Protocols for real-time delivery

To support end-to-end delivery of real-time traffic, UDP instead of TCP is usually applied as a transport protocol. However, the simple mechanism of UDP cannot guarantee real-time delivery and may starve TCP connections in the same network. Thus, additional protocols such as real-time protocol (RTP) and real-time transport protocol (RTCP) are needed to work over UDP. On top of RTP/RTCP, rate control protocol (RCP) is also needed for congestion control.

To date, many RCP protocols have been proposed for wired networks. They can be classified into two types: additive-increase multiplicative-decrease (AIMD)-based or equation-based. However, these protocols are not applicable to wireless networks due to existence of packet errors and link failures. Thus, differentiation between losses caused by congestion or wireless channels need to be taken into account with RCP. Various loss differentiation algorithms (LDAs) with congestion control are studied in [28], where only one wireless link is considered on the path between sender and receiver. It is shown in [28] that the hybrid LDA is the most effective. However, this result may not be applicable to WMNs, since multiple wireless links are on the path between receiver and sender.

An analytical rate control scheme is proposed in [6] for end-to-end transmission of real-time traffic over both wired and wireless links. However, the scheme has not considered factors such as the ad hoc architecture and mobility as in WMNs. Therefore, whether this scheme is applicable to WMNs needs to be researched further.

To date, few rate control schemes are available for mobile ad hoc networks. Recently, an adaptive detection rate control (ADTFRC) scheme has been proposed for mobile ad hoc networks in [49], 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 [49]. This may degrade the performance of the rate control scheme.

To date, no RCP has been proposed for WMNs. In addition, no effective RCPs for ad hoc networks can be adopted and tailored for WMNs. Thus, RCP for WMNs is a new research area.

10.3. Open research issues

In addition to the above mentioned open research issues, there exist several other problems which need investigation.

In order to reduce the impact of network asymmetry on TCP performance, cross-layer optimization is a challenging but effective solution, since 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 for a routing protocol to select an optimal path for both data and ACK packets but without increasing overhead. We also know that the link layer performance directly impacts packet loss ratio and network asymmetry. Thus, in order to reduce the possibility of network asymmetry, the MAC layer may need to treat TCP data and ACK packets differently. In addition, error control schemes may need to be enhanced in the MAC layer.

It is also important that the enhanced TCP has minimal impact on existing TCP. For WMNs, it is common that a network node will communicate with other network nodes outside of mesh networks such as the Internet. Thus, from an end node to another end node, both wireless and wired links may exist, which requires the enhanced TCP in WMNs and can work together with classical TCPs for wired networks. For example, the intermediate-layer concept of ATCP [92] can be adopted for WMNs.

Besides the Internet, WMNs will also be integrated with various wireless networks such as IEEE 802.11, 802.16, 802.15, etc. The characteristics of these networks may be significantly heterogeneous due to different network capacity and behaviors of error control, MAC, and routing protocols. Such heterogeneity renders the same TCP ineffective for all networks. Applying different TCPs in these networks will make the integration be complicated and costly. As a consequence, proposing an adaptive TCP is the most promising solution for WMNs. An adaptive transport protocol is proposed in [7] for an integrated network of wireless LANs, cellular networks, Internet backbone, and satellite networks. However, due to the hybrid ad hoc and infrastructure architecture, an integrated WMN is much different from the integrated network in [7]. Consequently, new adaptive transport protocols need to be proposed for an integrated WMN.

For real-time delivery, no existing solution from ad hoc networks can be adopted and tailored for the use of WMNs. Thus, brand-new RCPs need to be developed 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 for WMNs.

11. Application layer

Applications determine the necessity to deploy WMNs. Thus, it is always a key step to find out what existing applications can be supported by WMNs and what new applications need to be developed.

11.1. Applications supported by WMNs

Since numerous applications can be supported by WMNs, it is infeasible to have a complete list of them. Here, depending on the functions for WMNs, we categorize applications of WMNs into several classes:

- *Internet access*. Various Internet applications provide important timely information to people, make life more convenient, and increase work efficiency and productivity. For example,

email, search engine like Google, on-line actions like eBay, on-line purchase, chatting, video streaming, etc., have become an indispensable part of life. Thus, people are interested to subscribe the Internet. In a home or small/medium business environment, the most popular network access solution is still DSL or cable modem along with IEEE 802.11 access points. However, comparing with this approach, WMNs have many potential advantages: lost cost, higher speed, and easy installation. Therefore, Internet access will greatly motivate the development of WMNs.

- *Distributed information storage and sharing within WMNs*. For this type of applications, backhaul access to the Internet is not necessary. Users of these applications 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 mechanism, and query/retrieve information located in distributed database servers. Users within WMNs may also want to chat, talk on the video phones, and play games with each other. To have these applications work at the end-users, certain protocols must exist in the application layer.
- *Information exchange across multiple wireless networks*. Again, this type of applications does not need backhaul access to the Internet. For example, when a cellular phone talks to a Wi-Fi phone through WMNs, no Internet is needed. Similarly, a user on a Wi-Fi network may expect to monitor the status in various sensors in a wireless sensor network. All these applications must be supported by new algorithms or software in the application layer of the end-users.

11.2. Open research issues

There are mainly three main research directions in the application layer:

1. *To make existing Internet applications work under the architecture of WMNs.* Due to ad hoc and multi-hop wireless network architecture of WMNs, there is no way for protocols in the lower layers to 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. Such problems may fail certain applications working smoothly in a wired network, especially those with time-critical constraints. Therefore, algorithms in the application layer must be developed to improve the performance of real-time Internet applications over WMNs.
2. *To study application protocols for distributed information sharing in WMNs*. For example, for wired networks, application protocols are available for peer-to-peer information sharing, on-line gaming, etc. However, WMNs have much different characteristics than wired networks. Whether these protocols achieve a satisfactory performance in WMNs need to be investigated. In case the answer is negative, new application protocols need to be developed.
3. *To discover unique applications that utilize the advantages of WMNs.* Such applications must bring tremendous benefits to customers. Moreover, their functions cannot be accomplished by other existing networks. In such a way, WMNs will be enabled to be a unique networking solution instead of just another option of wireless networking. For example, if wireless sensor networks are integrated with WMNs, software tools can actually be developed for users in a home networking environment to remotely monitor, configure, and control all electronic devices, which makes home automation become a reality.

12. Protocols for network management

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

12.1. Mobility management

Mobility management consists of two important tasks: location and handoff management [10]. Location management handles location registration and call delivery, while handoff management

is responsible for handoff initiation, new connection generation, and data flow control for call handoff. The mobility management schemes developed for cellular [10] or mobile IP networks [11] could be useful for WMNs. However, the centralized scheme is generally not applicable on WMNs which are based on distributed and ad hoc architecture. Thus, distributed mobility management is a preferred solution for WMNs. Mobility management schemes of ad hoc networks are mainly comprised of two types: distributed [56] and hierarchical mobility management [125,30]. These schemes may not perform well for WMNs due to the specific features of WMNs. More specifically, the backbone of WMNs does not have high mobility as mobile nodes in ad hoc networks, but connections between all mesh routers are wireless. Mesh clients may constantly roam across different mesh routers. These features also render the mobility management schemes for cellular networks ineffective for WMNs. As a result, new mobility management schemes need to be developed for WMNs.

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

Mobility management is closely related to multiple layers of network protocols. The development of multi-layer mobility management schemes as in [43] is an interesting topic.

12.2. Power management

The goal of power management for WMNs varies. Usually, mesh routers do not have a constraint on power consumption; power management aims to control connectivity, interference [86], spectrum spatial-reuse, and topology [91]. If a single channel is used in each network node, the interference among the nodes directly impacts the spectrum spatial-reuse factor. Reducing transmission power level decreases the interference and increases the spectrum spatial-reuse efficiency [86]. However, more hidden nodes may cause performance degradation in MAC protocols. Thus, power management schemes are closely coupled with MAC protocols. Moreover, since connectivity affects performance of a routing protocol, power management is also crucial for the network layer.

In contrast to mesh routers, mesh clients may expect protocols to be power efficient. For example, some mesh clients are IP phones or even sensors; power efficiency is the major concern for them. Thus, it is quite possible that some applications of WMNs require power management to optimize both power efficiency and connectivity, which results in a complicated problem.

12.3. Network monitoring

Many functions are performed in a network management protocol. The statistics in the MIB (management information base) of mesh nodes, especially mesh routers, need to be reported to one or several servers in order to continuously monitor the network performance. Data processing algorithms in the performance monitoring software on the server analyze these statistical data and determine potential abnormality. In case any abnormal symptom is detected, the server reacts to take responses, e.g., triggering an alarm. Based on the statistical information collected from MIB, data processing algorithms can also accomplish many other functions such as network topology monitoring. The network topology of WMNs is not always fixed due to mobility in mesh clients or possible failures in some mesh routers. Thus, monitoring the network topology is a desired feature for WMNs.

A few network management protocols [121] have been proposed for ad hoc networks. However, the efficiency of these schemes needs to be improved for a large scale mesh network. In addition, in order to accurately detect abnormal operation of WMNs, effective data processing algorithms are needed. Also, how to quickly determine network topology is still an open question.

13. Security

Security is always a critical step to deploy and manage WMNs. Virtual private networking

(VPN) is possible over wireless LANs. It is usually implemented with standard key encryption algorithms for tunneling such as IPSec to provide secure virtual paths along the shared networks.

Security in terms of authentication and authorization is not a big issue for wireless LANs; some wireless LAN commercial system implementations provide authentication, authorization, and accounting (AAA) services directly over the wireless LAN access point or via gateways to take care of this issue. AAA is usually performed through a centralized server such as RADIUS (remote authentication dial-in user service). However, the centralized scheme is not scalable in WMNs. Similar to mobile ad hoc networks, WMNs still lack efficient and scalable security solutions because their security is easier to be compromised due to [143,25]: vulnerability of channels and nodes in the shared wireless medium, absence of infrastructure, and dynamic change of network topology. The attacks may advertise routing updates in [60] and [145] for DSR and AODV, respectively. Another type of attacks is packet forwarding, i.e., the attacker may not change routing tables, but the packets on the routing path may be lead to a different destination that is not consistent with the routing protocol. Moreover, the attacker may sneak into the network, and impersonate a legitimate node and does not follow the required specifications of a routing protocol [37]. Some malicious nodes may create wormhole and shortcut the normal flows among legitimate nodes [61].

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 cause the network to be always congested by these malicious nodes [55].

Attackers may sneak into the network by misusing the cryptographic primitives [22]. In a cryptographic protocol, the exchange of information among users occurs frequently. The users employ a fair exchange protocol which depends on a trusted third party. However, this trusted party is not available in WMNs due to lack of infrastructure. Thus, another exchange scheme, called *rational exchange*, must be used. Rational exchange ensures that a misbehaving party cannot gain anything from misbehavior, and thus, will not have any incentives to misbehave [26].

The key management is one of the most important tasks for network security. However, the key management for WMNs becomes much more difficult, because there is no central authority, trusted third party or server to manage security keys. Key management in WMNs need to be performed in a distributed way. A self-organization scheme was proposed in [63] to distribute and manage the security keys. In this self-organizing key management system, certificates are stored and distributed by users themselves. When the public keys of two users need to be verified, they first merge the local certificate repositories and then find the appropriate certificate chains within the merged repositories that can pass this verification.

To enhance security of WMNs, two strategies need to be adopted. Either to embed security mechanism into network protocols such as secure routing and MAC protocols or to develop security monitoring and response systems to detect attacks, monitor service disruption, and respond quickly to attacks. To date, many secure protocols have been proposed [60,145]. However, their role of defending attacks is very limited, because schemes located in a single protocol layer cannot solve problems in other layers. However, security attacks in a network may come simultaneously from different protocol layers. Thus, a multi-protocol layer security scheme is desired for network protocols.

For a security monitoring system, a cross-layer framework also needs to be developed. A framework of intrusion detection in ad hoc networks is proposed in [146]. However, how to design and implement a practical security monitoring system, including cross-layer secure network protocols and various intrusion detection algorithms, is a challenging research topic.

14. Timing synchronization

Timing synchronization is critical for the performance of network protocols, e.g., power management schemes and MAC protocols.

A power management scheme usually depends on the synchronized time to determine when a network node needs to be turned on/off or to enter sleep mode according to certain performance criteria. For WMNs, TDMA MAC protocols are usually difficult to implement because network nodes are not accurately synchronized. Without enough accuracy in timing synchronization, a large percentage of bandwidth must be used as guard time in TDMA MAC.

Synchronization among nodes has been specified as timing synchronization function (TSF) in IEEE 802.11 for both infrastructure and ad hoc modes. To improve performance of the standard synchronization scheme, especially the scalability, some solutions have been proposed in [62,87]. However, the TSF in IEEE 802.11 standard and in [62,87] cannot be directly applied to large WMNs, because the synchronization information may take a long time.

To date, timing synchronization for WMNs lacks an effective approach to achieve satisfactory accuracy. Thus, it is necessary to develop better power management schemes or MAC protocols that do not demand high accuracy of timing synchronization.

15. Cross-layer design

Traditionally, different protocol layers are required to be transparent from each other. This makes the protocol development and implementation be a simple and scalable process. However, the methodology of layered protocol design does not necessarily lead to an optimum solution for wireless networks. For example, the physical channel in a wireless environment 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 as expected by higher layers. Therefore, higher layer protocols will be inevitably affected by the unreliable physical channel. To further improve the performance of a wireless network, MAC, routing, and transport protocols have to work together with the physical layer. In addition, MAC, routing, and transport protocols also need to work collaboratively among themselves. Such interactions demand a cross-layer design among different protocols.

In WMNs, because of the ad hoc feature, network topology constantly changes due to mobility and link failures. Such dynamic network topology impacts multiple protocol layers. Thus, in order to improve protocol efficiency, cross-layer design becomes indispensable. For instance, a MAC protocol for WMNs may include a mechanism for network topology control and self-organization. Such information can be directly shared by a routing protocol. To avoid broadcast storming in a routing protocol, the underlying MAC protocol can optimize the procedure of transmitting signaling messages initiated by routing protocols.

Cross-layer design can be performed in two ways. The first way is to improve the performance of a protocol layer by considering 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 the link quality to a routing protocol as an additional performance metric for the routing algorithms. The second way 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 advantage of the first way is that it does not totally abandon the transparency between protocol layers, while the second way will totally lose this advantage. However, the second way can achieve much better performance by considering an optimized interaction between protocol layers.

Cross-layer design can significantly improve network performance [20,84,32]. However, certain issues must be considered when carrying out cross-layer protocol design [77]: cross-layer design have risks due to loss of protocol layer abstraction, incompatibility with existing protocols, unforeseen impact on the future design of the network, and

difficulty in maintenance and management. Thus, certain guidelines need to be followed [77].

16. Testbeds and implementations

Numerous testbeds have established to carry out research and development for WMNs.

16.1. Academic research testbeds

One of the earliest mesh network testbeds is Carnegie-Mellon University's mobile ad hoc network testbed [95]. It consists of seven nodes: two stationary nodes, five car mounted nodes that drive around the testbed site, and 1 car mounted roving node that enters and leaves the site. Packets are routed between the nodes using the DSR protocol [73] which also integrates the ad hoc network into the Internet via a gateway. They experimented with the network behavior under different levels of traffic load, including audio and video streams, and designing protocol enhancements to provide these streams with QoS promises. Interesting results were observed in the experiments:

- Local (i.e., link layer) retransmission algorithms is a critical part of any multihop ad hoc network. If the retransmission algorithms implemented above the link layer, it must be adaptive in order to accommodate network congestion and periods of high contention in the wireless channel.
- Delivering routing protocol control packets as rapidly as possible is important for high end-to-end performance, and this implies that packets with routing implications should be scheduled for transmission ahead of users data packets.

MIT's *Roofnet* is an experimental multi-hop 802.11b mesh network [4,5]. It consists of about 50 wireless nodes to interconnect the Ethernet networks (with Internet gateways) in apartments in Cambridge, MA. A primary feature of Roofnet is that it requires no configuration or planning. One consequence of an unplanned network is that each node can route packets through any of a large number of neighbors, but the radio link to each neighbor is often of marginal quality; finding the best multi-hop routes through a rich mesh of marginal links turns out to be a challenge. The average TCP throughput and latency of all Roofnet nodes to their nearest gateway were measured in April 2004. When 1 hop is considered for 18 nodes, the average throughput and latency are 357.2 kbytes/s and 9.7 ms. However, when 4 hops are considered for 7 nodes, the average throughput is only 47.3 kbytes/s and the average latency is 43.0 ms. The low multihop throughput reflects the problem typical in all 802.11 MAC based multihop networks.

University of Illinois at Urbana-Champaign has reported a 4-node multi-channel 802.11b testbed [119]. Each node is equipped with 2 cards whose channels were determined based on the load-aware channel assignment algorithm. The multi-channel network achieves 2.63 times the throughput as compared to the single channel network. The number of non-overlapping channels in 802.11b standard, i.e., 3, is the limiting factor for this performance. The performance, however, does not reach 3 times of the single-channel network performance because of the inter-channel interference that cannot be completely eliminated. Substantial interference was observed between two 802.11b cards placed on the same machine despite operating on non-overlapping channels. In addition, the degradation due to inter-channel interference was found independent of the guard band. One way to reduce the interference is to use USB cards instead of PCI/PCMCIA cards and place them side-by-side in similar configuration as in Orinoco AP-1000 access points. Another possibility is to equip cards with external antennas and place the external antennas slightly away from each other. Yet another option is to use the upcoming Engim chipsets which solve the interference problem at RF-level [44].

California Institute for Telecommunications and Information Technology (Cal-$(IT)^2$) has established a basic Wi-Fi MAC development platform called *CalRADIO-I* [132]. This is a Wi-Fi research and development device that consists of a TI 5410 DSP, a 16-bit stereo CODEC, external Flash and SRAM memories, and support of a

RF LAN module. It provides a convenient platform for development of RF radios from the physical layer up to the application layer. The key benefit of the board is that all aspects of the MAC are coded in *C* language and, therefore, are altered easily for research in queueing, security, power management, MIMO, cognitive radio, and so forth. It also utilizes basic Symbol Technologies' Wi-Fi test board as the base for modifying board and re-spinning to incorporate new features. CalRADIO-I is evolving into a CalRADIO-II develop platform with basic DSP board and multiple RF front-end modules such as 802.11x, 802.16, cell and general RF. This will eventually allow the capability of publishing standards in software/firmware and hardware.

The Broadband and Wireless Network (BWN) Lab at Georgia Institute of Technology has recently built a testbed of WMNs, as shown in Fig. 13. The WMN, called *BWN-Mesh*, consists of 15 IEEE 802.11b/g based mesh routers, among which several of them are connected to the next generation Internet testbed (also available in the BWN Lab) as backhaul access to the Internet. The testbed consists of laptops and desktops equipped with IEEE 802.11b and IEEE 802.11g cards located in various rooms on the floor where the BWN Lab resides. By changing the topology of the network, experiments investigating the effects of inter-router distance, backhaul placement and clustering are performed along with mobility experiments using the laptops in the testbed.

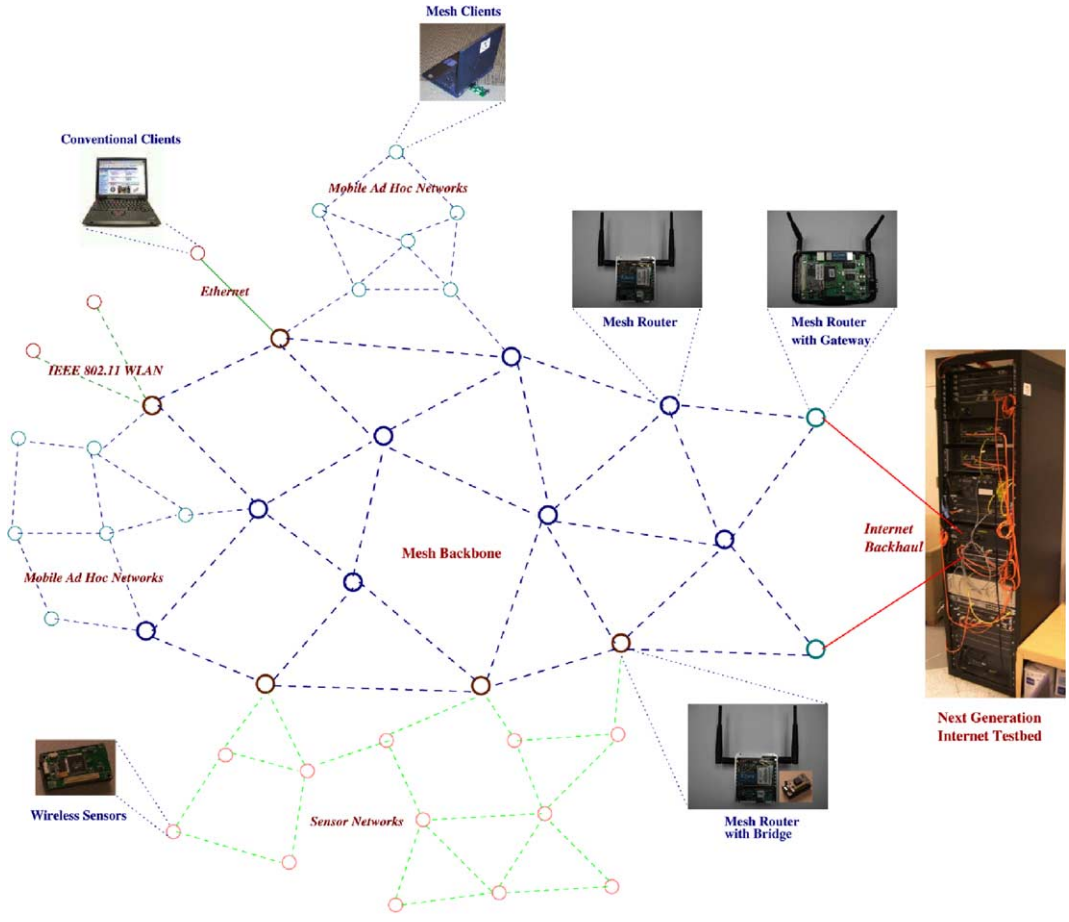

Fig. 13. *BWN-Mesh* testbed at Georgia Tech.

Moreover, experiments with existing protocols (i.e., TCP, AODV, and IEEE 802.11g as transport, routing, and MAC protocols) for *BWN-Mesh* testbed have demonstrated that these protocols do not perform well in terms of end-to-end delay and throughput in WMNs. Currently, the research is focused on adaptive protocols for transport layer, routing and MAC layers and their cross-layer design [24]. These protocols are developed and evaluated on the *BWN-Mesh* testbed. The approaches being explored in the BWN lab are not merely limited to Wi-Fi mesh networks but also applicable for wireless sensor networks (WSNs) and wireless sensor and actor networks (WSANs). Thus, the *BWN-Mesh* testbed is integrated with the already existing BWN Sensor Network Testbed, which consists of MICA motes, with TinyOS distributed software operating system, and light, temperature, acoustic actuator, magnometer, and accelerometer sensors. In align with this effort, BWN Lab is also trying to integrate the current Wi-Fi mesh networks with other wireless networks such as WiMAX. Consequently, this integrated testbed will enable the design and evaluation of protocols applicable to heterogeneous wireless networks including WMNs, next generation Internet, WSNs, WSANs, and WiMAX.

16.2. Industrial practice

Microsoft Research Lab (MSR) implements ad hoc routing and link quality measurement in a software module called the mesh connectivity layer (MCL) [101]. Architecturally, MCL is a loadable Windows driver. It implements a virtual network adapter, so that the ad hoc network appears as an additional (virtual) network link to the rest of the system. MCL routes by using a modified version of DSR called LQSR. MCL is a routing protocol well-suited for low mobility, unconstraint power consumption and small diameter networks. The MCL driver implements an interposition layer between the link layer and the network layer. To higher layer software, MCL appears to be just another Ethernet link, albeit a virtual link. To lower layer software, MCL appears to be just another protocol running over the physical link. This design has several significant advantages. First, higher layer software runs unmodified over the ad hoc network. In Microsoft's testbeds, both IPv4 and IPv6 can run over the ad hoc network. No modification to either network stack is required. Network layer functionality (for example ARP, DHCP, and Neighbor Discovery) works fine. Second, the ad hoc routing runs over heterogeneous link layers. Microsoft's implementation supports Ethernet-like physical link layers (e.g., IEEE 802.11 and 802.3) but the architecture accommodates link layers with arbitrary addressing and framing conventions. The virtual MCL network adapter can multiplex several physical network adapters, so that the ad hoc network can extend across heterogeneous physical links. Third, the design can support other ad hoc routing protocols as well.

A variety of research and development at Intel are geared toward understanding and addressing the technical challenges of multi-hop mesh networks. Early work at the Intel Research-Berkeley Lab, affiliated with the University of California, Berkeley, has resulted in small sensor motes [70] which form self-configuring, low-cost adaptive networks. Additional work within Intel's Network Architecture Lab is aimed at overcoming many of the challenges faced by mesh networks. Low-cost and low-power access point prototypes, or nodes, have been developed to enable further research on security, traffic characterization, dynamic routing and configuration, and QoS problems. A demonstration was discussed in various occasions [71], consisting of a collection of Centrino laptop computers and IXP425 network processor based routers running AODV and 802.11b MAC protocols. The testbed results confirm that 802.11 MAC limits full exploitation of multihop throughput. As a means to enhance multihop throughput, it advocates spatial-reuse through carrier sensing threshold tuning [53]. Another potential solution experimented was the concept of heterogeneous networks: an 802.11 mesh network comprised of four high-end nodes, such as Intel XScale based nodes, is overlaid on a 50-sensor node (motes) network scattered throughout a large conference room. Sensor data can enter and exit the 802.11 backbone at multiple interchanges (the XScale nodes) in order to bypass the intermediate sensors. This should enable faster trips across the network

and result in improved performance since the number of nodes that the data has to pass through is much lower, leading to improved reliability and lower energy consumption [70]. This experiment has shown that, without the top level mesh network (XScale nodes), the average data age doubled, from approximately 10 s to 20–25 s, and the network lifetime increased by 20%.

Nortel's commercial roll out of the WMN products [106] includes wireless access point (WAP) which is a dual radio system supporting a 2.4 GHz access link and a 5 GHz transit link, equipped with smart antennas. Along with Nortel's wireless gateway routers and a network management system, WAPs can be used to wirelessly backhaul data traffic to the wired network or servers for an enterprise or carrier network. The WAP transit link employs an 802.11a standard physical layer, and an inter-AP meshing protocol above the MAC layer for transit link discovery, establishment, monitoring, maintenance, and re-establishment. It also performs automatic assignment of channels according to local conditions and access point neighborhood. The transit link uses an elevated dual-polar antenna with multiple degrees of freedom: beam, frequency, polarization, and burst time. Having multiple beams alleviates deployment difficulties. The WAP access link uses an 802.11g standard physical layer with an elevated, dual-polar, diversity switched antennas. Access Link coverage is typically less than the reach of a transit link. The user devices use standard 802.11b/g NIC and software to access the network. The Nortel mesh network is a sophisticated, carrier class quality but expensive system. Multiple field trials have been reported since late 2003.

MeshNetworks' initial attempt to commercializing mesh technology was its quadrature division multiple access (QDMA) radio platform. [99]. The QDMA radio is designed for mobile ad hoc broadband networking. It uses multi-channel MAC and PHY to overcome the effects of Doppler shifting, rapid Raleigh fading and multipath encountered in a mobile system. The MeshNetworks' scalable routing protocol [100] is implemented above QDMA radios. The scalable routing technology utilizes a hybrid ad hoc routing algorithm that combines both proactive and reactive routing techniques. To adapt the routing protocol to a given radio platform, adaptive transmission protocol (ATP) is implemented to tightly bind the scalable routing protocol to the underlying radio platform. MeshNetworks provides a software-only overlay solution that lets native 802.11b clients in existing networks work in mesh-mode. While it will not add any mobile broadband capabilities beyond what 802.11b can already support, it will extend the range and link robustness of existing Wi-Fi networks by allowing mesh-style multi-hopping. Security features in MeshNetworks' QDMA-based systems include a hardware firewall on a chip that makes it impossible for a client to access somebody else's packets. This feature will not be available in retrofitted 802.11 networks using the software overlay technology. However, other approaches such as route diversity will help resolve security issues.

Tropos Networks employs a cellular Wi-Fi network architecture to support ''infrastructure mesh'' networking [129], using its a layer-3 network operating system (NOS) called Tropos Sphere, that runs on standard 802.11 hardware and software. Tropos Sphere operates on every (small sized) Tropos Wi-Fi cell and contains the key communications, path selection, and security functions that allow the Wi-Fi cells to inter-operate and form a completely wireless network like a wireless routed LAN. Tropos uses a lightweight control protocol for supporting a large number of Wi-Fi cells. It uses a proprietary predictive path optimization protocol to improve end-user throughput and continuously optimize performance to compensate for the changing RF environment. This protocol is called predictive wireless routing protocol (PWRP), which is analogous to traditional wired routing protocols such as open shortest path first (OSPF). However, PWRP does not use routing tables or rely on hop-count only to select transmission paths. Rather, it compares packet error rates and other network conditions to determine the best path at a given moment. Since the system is largely a layer-3 solution that relies on the standard 802.11 MAC protocol for a large mesh network, many of the throughput performance impairments remain unresolved.

PacketHop's core technology was developed in the SRI International lab [107]. It consists of a network controller, performing gateway, QoS, security, and roaming functions, a network management system, and the Windows software for ad hoc mesh routing. This is largely a layer-3 solution that runs on 802.11 and multi-mode broadband radios. PacketHop is in collaboration with Nortel to complement Nortel's "infrastructure mesh" solution with its ad hoc meshing capability.

Kiyon is in conduction field trials with building automation and "small office home office" (SOHO) customers of its broadband wireless mesh routers [80]. Its technology is a layer-2/3 solution that implements a hybrid CSMA/CA and distributed TDMA MAC protocol atop an 802.11g/a physical layer. This is tightly coupled with a multi-metric "Attribute Routing" protocol, aiming at high and steady multihop throughput in a mesh network. As the new generation 802.11 radios adopt the soft MAC approach, e.g., Atheros, Broadcom and more recently Intel, Kiyon's enhanced MAC/routing protocols can be implemented in host software and downloaded into these standard 802.11 chipsets at runtime. Kiyon supports both infrastructure and client mesh, stationary or mobile wireless networks.

In a Kiyon mesh network, a number of routers form a broadband backbone of the network. Each of the routers is equipped with Kiyon's routing and MAC protocol software plus a standard IEEE 802.11g/a radio. For client access to the broadband backbone, several options can be adopted. The first option is called the "wired host route", in which a client can connect to the backbone via an Ethernet connection. Any IP capable devices (e.g., a RFID reader, BACnet controller or database server) can be connected to the wireless network this way. No software modification on the client is required. The second option is called the "wireless host route", in which a client device connects to the wireless network via a wireless LAN interface such as an 802.11 b/g/a NIC. In this arrangement, the client is "homed" on one of the routers in the network that satisfies the defined routing metric, such as signal strength. The client has the option to run Kiyon's software or not. With Kiyon's software, a client becomes a full function router. Without Kiyon's software, a client device running standard 802.11 station software can originate and terminate traffic. Mobility of client devices is supported in both cases. The third option is a form of hierarchical network, in which a number of standard 802.11 access points serve as the access layer for client devices. Each of these access points is attached to one of the backbone routers via an Ethernet connection.

17. Standard activities

17.1. IEEE 802.11 mesh networks

Currently, IEEE 802.11 wireless networks can achieve a peak rate of 11 Mbps (802.11b) and 54 Mbps (802.11a/g). Also under development is a high-bandwidth extension to the current Wi-Fi standard. Researchers expect 802.11n to increase the speed of Wi-Fi connections by 10–20 times. Although many home users will not benefit from the additional speed right away, because of limitations on their cable or DSL connections, enterprises are hoping the technology will allow them to reduce the burden of laying and maintaining Ethernet cabling throughout the building.

There are many academic testbeds and commercial deployment of mesh networks using IEEE 802.11 wireless LAN technology. However, mesh networking is at the same stage as wireless LANs were in the early 1990s; they are expensive and proprietary. To become commoditized, the economic pressures are driving the standard processes. Furthermore, protocols for 802.11 ad hoc mode are insufficient for multi-hop and mesh networking, because of lack of scalability in the MAC protocol, resulting in poor network performance. A working group within IEEE 802.11, called 802.11s, has been formed recently to standardize the extended service set (ESS) [57]. 802.11s aims to define MAC and PHY layers for mesh networks that extended coverage with no single point of failure. In such networks, 802.11 cellular wireless LAN access points relay information from one to another in a router-like hop-by-hop fashion.

As users and access points are added, the capacity increases, as in the Internet, giving rise to a

scalable and redundant architecture. Early discussions in this working group include definition of WMNs, usage cases, QoS, architecture specifications, security, routing protocols, and development of new MAC protocols. Several task groups have been formed to tackle these issues.

Wi-Fi mesh networking can be implemented in two basic modes: infrastructure and client meshing. The former is an infrastructure ESS mesh, in which access points are interconnected through wireless links that enable automatic topology learning and dynamic path configuration. Clients are associated with access points and need not be aware of the mesh. Infrastructure meshing creates wireless backhaul mesh among access points or wireless routers. This reduces system backhaul costs while increasing network coverage and reliability. To provide an IEEE 802.11 ESS Mesh, 802.11s will define an architecture and protocol based on the IEEE 802.11 MAC to create an IEEE 802.11 wireless distribution system (WDS) that supports both broadcast/multicast and unicast delivery at the MAC layer using radio-aware metrics over self-configuring multi-hop topologies. From the view of access points, the infrastructure meshing also forms an ad hoc network among access points. The other mode of meshing, i.e., client meshing, is a layer-3 ad hoc IBSS (independent basic service set), in which all devices operate in ad hoc mode in a flat network, using IP routing. There is no distinction between access points and client. Client meshing enables wireless peer-to-peer networks to form between and among client devices and does not require any network infrastructure to be present. In this case, clients can hop through each other to reach other clients in the network. To maximize the benefit that meshing can offer, both modes should be supported simultaneously and seamlessly in a single network.

17.2. IEEE 802.15 mesh networks

IEEE 802.15.3a standard [65] is based on MultiBand OFDM Alliance (MBOA)'s physical layer that uses ultra wide band (UWB) to reach up to 480 Mbps. A competing proposal of a Direct Sequence-UWB (DS-UWB) claims support for up to 1.3 Gbps. It is intended for high throughput personal area networking (PAN) that has communication distances of around 10 m (or less), with applications in home networking space, with imminent wireless extensions to USB, IEEE 1394, and with the capability to address the convergence of PC, consumer electronics and IP mobile phones. Vendors planning to produce 802.15.3a products have formed the WiMedia Alliance [138], a branding and testing organization that will certify standards compliance.

UWB networks hold many advantages over other wireless networks, such as covert communications, low power and cost requirement, accurate location information, and extra high bandwidth. However, the communication range is rather short. Mesh networks have been predicted to be the killer application for UWB radio systems. A new MAC proposed by MBOA, which deviates substantially from the original IEEE 802.13a MAC proposal, has added strong support for mesh networking and mobility, paving the way for UWB to enter the enterprise network. The MBOA MAC uses piconet structure, combined with a decentralized resource-handling ability to allow for the reservation of timeslots for 802.15.3-like TDMA for high priority connections requiring determinism while assigning contention-based, best-effort access periods.

IEEE 802.15.4 is intended for telemetry with low data rate, long battery life and low device cost requirements. The ZigBee Alliance [148] is developing higher-level protocols that will run over 802.15.4 MAC and PHY layers that operate in unlicensed bands worldwide. Raw data rates of 250 Kbps can be achieved at 2.4 GHz (16 channels), 40 Kbps at 915 MHz (10 channels), and 20 Kbps at 868 MHz (1 channel). The transmission distance is expected to range from 10 to 75 m, depending on power output and environmental characteristics. The ZigBee network layer supports multiple network topologies including star, cluster tree, and mesh. In a mesh topology, a special node called coordinator is responsible for starting the network and for choosing key network parameters. The routing algorithm uses a request–response protocol to eliminate sub-optimal routing.

Recently a new working group, i.e., IEEE 802.15.5, is established to determine the necessary

mechanisms in the physical and MAC layers to enable mesh networking [65] in wireless PANs.

17.3. IEEE 802.16 mesh networks

While IEEE 802.11 networks fulfill the need for data services in a local area (i.e. last several hundreds of feet), IEEE 802.16 aims at serving the broadband wireless access in metropolitan area networks [66] (i.e., last mile), supporting point-to-multipoint connection oriented QoS communications to extend fiber optic backbones. The original 802.16 standard operates in the 10–66 GHz frequency band and requires line-of-sight towers. The 802.16a extension, ratified in January 2003, uses a lower frequency of 2–11 GHz, enabling non-line-of-sight connections. With 802.16a, carriers will be able to connect more customers to a single tower and substantially reduce service costs. To allow consumers to connect to the Internet while moving at vehicular speeds, researchers are developing an extension to IEEE 802.16 standard called 802.16e.

WiMAX is the commercialization of the maturing IEEE 802.16 standard. WiMAX antennas will be able to beam high-speed Internet connections to homes and businesses miles away, eliminating the need for every building to be wired to the Internet. WiMAX is ideal for many neighborhoods that are too remote to receive Internet access via cable or DSL, and for anyplace where the cost of laying or upgrading landlines to broadband capacity is prohibitively expensive. In areas with cable or DSL access, WiMAX will provide consumers with an additional, and possibly cheaper, alternative. Along with the IEEE 802.16 standard, WiMAX is envisioned to provide long distance both line of sight and non-line of sight (NLOS) broadband wireless access (BWA).

The 802.16 mesh in the current standard draft has several limitations:

- The 802.16 mesh has limited scalability. The mesh can only support around 100 subscribers due to centralized scheduling message structures.
- The 802.16 mesh is based on a connectionless MAC, so QoS of real-time services is difficult to guarantee [40].
- It is assumed no interference between nodes that are two hops away. Thus, the 802.16 mesh suffers from the hidden terminal problem.

To enhance the 802.16 mesh, several proposals have been submitted to the standard committee [19]. A group within 802.16, the Mesh Ad Hoc committee, is investigating ways to improve the performance of mesh networking. It is understood that only a small amount of meshing is required to see a large improvement in the coverage of a single base station. More importantly, the following issues are considered in specifying the 802.16 mesh MAC protocol:

- *Avoiding hidden terminal collisions*,
- *Selection of links*,
- *Synchronization*,
- *Power versus data rate tradeoffs, and*
- *Greater routing-MAC interdependence.*

18. Conclusion

The capability of self-organization in WMNs reduces the complexity of network deployment and maintenance, and thus, requires minimal up-front investment. The backbone of WMNs provides a viable solution for users to access the Internet anywhere anytime. It can also enhance the reliability of the mobile ad hoc network of mesh clients. WMNs enable the integration of multiple wireless networks.

WMNs can be built up based on existing technologies. Some companies already have products for sale, while other companies have started to deploy WMNs in various application scenarios. However, field trials and experiments with existing WMNs prove that the performance of WMNs is still far below what they are expected to be. As explained throughout this paper, many open research issues need to be resolved:

- *Scalability*. Based on existing MAC, routing, and transport protocols, the network performance, indexed by throughput, end-to-end delay, and fairness, 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 capacity of network nodes. Typical approaches include applying 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 the relative performance over the increased network capacity is not actually improved. Therefore, in order to achieve scalability, it is essential to develop new MAC, routing, and transport protocols for WMNs.

- *Self-organization and self-configuration*. Self-organization and self-configuration require all protocols in WMNs to be distributive and collaborative. Otherwise, WMNs will lose the autonomic feature. However, current WMNs can only partially realize this objective.
- *Security*. Due to wireless ad hoc architecture, WMNs are vulnerable to security attacks in various protocol layers. However, current security approaches may be effective to a particular attack in a specific protocol layer, but lack a comprehensive mechanism to prevent or counter attacks in different protocol layers.
- *Network integration*. Current WMNs have very limited capabilities of integrating heterogeneous wireless networks. Integrating multiple heterogeneous wireless networks is still an on-going task for WMNs, due to the difficulty in building multiple wireless interfaces and the corresponding gateway/bridge functions in the same mesh router. Software radios may be the ultimate solution to this problem.

Protocol improvement relying on single layer cannot entirely solve all the existing problems. All protocols ranging from physical to application layers need to be improved or re-invented, and the cross-layer design among these protocols is needed in order to reach the optimal performance.

WMNs are a promising technology for next generation wireless networking. Many application scenarios are stimulating its rapid development. However, to strengthen the market penetration and secure the success of WMNs, more research is needed.

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