A Study on Medium Access Control Protocols in Wireless Mesh Networks

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Abstract— **Wireless mesh networks have both ad hoc and infrastructure modes to provide multihop data transmission for mesh clients. Because of the hybrid network architecture, the medium access control protocols designed for centralized or distributed networks cannot be directly applied in wireless mesh networks as they severely degrade the network performance. This paper first analyze the network architecture and identify some technical challenges on the design of medium access protocols in wireless mesh networks. The corresponding solutions are reviewed, followed by a brief discussion of some open issues.**

***Index Terms*—WMN, MAC, Design Issues, Technical Challenges.**

I. Introduction

In recent years, wireless mesh networks (WMN) [1, 2], together with related applications and services, have been actively researched. Targeting primarily for solving the well-known last mile problem for broadband access [3, 4], WMNs aim to offer high-speed coverage at a significantly lower deployment and maintenance cost. WMNs are different from other wireless networks. Usually WMNs consist of two kinds of nodes: mesh routers and mesh clients. Mesh routers have multiple wireless interfaces, which can be built on either the same or different wireless access technologies. With the built-in gateway/bridge functionalities, mesh routers can incorporate with other types of networks. Mesh clients have two roles: being an end client and being a router in the network. However mesh clients can only take on the minimum routing functions. For instance, gateway/bridge functions are not applicable on mesh clients. Consequently, mesh clients only have one wireless interface.

The architecture of WMNs can be grouped into three categories [1]: Client Architecture, Infrastructure/Backbone Architecture, and Hybrid Architecture.

Client Architecture only contains client nodes, as shown in Fig. 1. These client nodes play double roles of network routers and network end-users. No mesh routers are used in this type of networks. Client mesh architecture provides peer-to-peer communications among all the nodes in the network. This type of network is more like a conventional Ad-Hoc network since only one radio technology is usually involved. Special requirements such as software/hardware installation are needed for client nodes in WMNs, since these nodes have to perform the routing functions.

Infrastructure/Backbone Architecture contains both mesh routers and mesh clients nodes, as shown in Fig. 2. Mesh routers form the infrastructure backbone for clients and bring connectivity to them. Mesh routers perform functions such as routing, as well as self-configuring and self-healing. Moreover, various radio technologies, such as IEEE 802.11, IEEE 802.16, can be used with this type of meshing architecture. Hence, with the built-in gateway/bridge functionality of mesh routers, infrastructure meshing architecture provides an interface for integrating existing wireless networks. Multiple wireless interfaces are enabled in an infrastructure/Backbone architecture. Conventional clients that have Ethernet interface can be connected to mesh routers through the Ethernet interface. If the conventional client uses the same radio, then it can directly communicate with mesh routers. Otherwise, the conventional client has to communicate with its Base Station (BS) that is connected to mesh routers via Ethernet interface.

Hybrid Architecture, as the name suggested, combines the above two types of meshing architecture, as shown in Fig. 3. In this type of architecture, client nodes communicate with each other via mesh routers, or via peer-to-peer among clients themselves. At the same time, the infrastructure backbone makes the connectivity possible to other existing wireless networks, such as Wi-Fi, WiMax, WPAN and WSNs. This architecture is the model for the future generation networking.

The remainder of the paper is organized as follows: In section II, the medium access control protocol is presented in the context of WMN. The MAC issues of WMN are presented in section III. Existing MAC protocols for WMNs are reviewed in section IV. Finally, the paper concludes with section V.

II. Medium Access Control

When a network node is equipped with physical layer techniques for signal transmission and reception, it basically has the point-to-point communication capability. However, this is insufficient for networking among multiple nodes, for several reasons. First of all, an interface is needed between

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physical and higher layer protocols in order to interpret bit streams and convert them into packets or vice versa. Secondly, operation mechanisms and algorithms are required to coordinate transmission and reception of packets among many nodes with the objective of improving network performance. This type of function is called medium access control (MAC). Thirdly, errors can still occur in bits or packets even though the most advanced channel coding algorithms are applied. This is particularly true for wireless networks because of variations of link quality, interference, and many other factors. As a result, additional error control is usually desired on top of physical layer.

The key task of a MAC protocol is to coordinate the process of sharing the same medium among multiple users with the objective of achieving certain performance goals. Depending on which network node takes care of the coordination of medium access, MAC can be classified into two major types: centralized MAC and distributed MAC. In a centralized MAC protocol, the entire process is controlled and coordinated by a centralized node, and all other nodes must rely on this node to access the network. Many wireless networks lie in this category. For example, cellular networks, infrastructure mode wireless LANs, satellite networks, etc. However, in multihop wireless networks, distributed MAC is preferred, because the network itself is distributed in essence. If a centralized MAC is used for these networks, it lacks enough efficiency owing to the need for maintaining the centralized control among multiple nodes. This also inhibits the scalability of the MAC protocol. As a result, distributed MAC is extremely necessary for WMNs. However, it is obvious that designing a distributed MAC is a much more challenging task than designing a centralized MAC.

As the WMN has a hybrid structure of centralized and ad hoc architecture, the MAC layer access mechanisms proposed for wireless ad hoc, sensor and WLAN are potentially suitable for mesh networks. There are a number of papers that study the possibility of implementing existing MAC protocols to WMN, e.g. IEEE 802.11 MAC protocols. The existing MAC protocols have been well studied and analyzed by many researchers, and classified by several methods. From the aspect of channel division, they are classified into single channel and dual/multiple channels, whereas from the aspect of session initiator, they are classified into sender initialized and receiver initialized.

In wireless mesh networking, the MAC protocol plays an important role in coordinating channel access among mesh nodes. Most traditional medium access protocols are designed for nodes with omnidirectional antennas and for sharing a single channel. Examples include Aloha, Slotted Aloha, carrier sense multiple access (CSMA), and CSMA with collision avoidance (CSMA/CA). The two MAC protocols defined in the IEEE 802.11 standards, i.e., the IEEE 802.11 MAC protocol and the IEEE 802.11e quality of service (QoS) enhancement MAC protocol, are single-channel MAC protocols designed for nodes with omnidirectional antennas. Even though single-channeled MAC protocols are robust and easy to implement, WMNs based on such rudimentary MACs may suffer low throughput due to collisions and interference caused by multihop routing. For instance, the maximum throughput for a daisy-chained network could be only one-seventh of the nominal link bandwidth when the IEEE 802.11 MAC is used [5]. As a result, congestion in such networks would be more frequent and persistent, making it a great challenge to support bandwidth-intensive applications (e.g., video communications).

To address the low throughput problem in multihop mesh networks, MAC protocols that explore alternative physical layer technologies, such as directional antennas (including smart antennas), have been proposed. The basic idea is to reduce the transmitter's interference range and to improve channel spatial reuse by using directional antennas. Another effective solution to the low throughput problem is to use multiple channels at mesh nodes, allowing concurrent transmissions on these channels. In fact, many current physical layer standards do provide multiple channels at the physical layer. For example, the IEEE 802.11b PHY standard for wireless local area net-works (WLANs) provides three orthogonal channels (channel 1, 6, and 11) for use in the United States, while IEEE 802.11a provides 12 nonoverlapping channels. Such orthogonal channels could be used simultaneously in a neighborhood without interfering with each other. Consequently, there has been substantial effort on developing such multichannel MAC protocols that can efficiently assign channels to mesh nodes and coordinate the sharing of these channels.

III. MAC Issues In WMNs

The major function of MAC in WMNs is to arbitrate access to the open and shared medium, with the objective of maximizing network capacity and achieving some level of fairness among users. In particular, there are several PHY/MAC attributes that can be used to improve spatial reuse, mitigate interference and maximize network capacity: (i) the transmit power each node uses for communications, (ii) the carrier sense threshold each node uses to determine if the shared medium is idle, (iii) the channel on which the node transmits, and (iv) the time intervals in which each node gains access to the channel. Note that the carrier sense threshold specifies the received signal strength above which a node determines that the medium is busy and will not attempt for transmission. The first two attributes control the sharing range of the wireless medium in the spatial domain and ultimately the degree of spatial reuse. The third attribute exploits use of non-overlapping channels to mitigate interference. The last attribute leverages temporal/spatial diversity and aims to schedule transmission of packets that may potentially interfere with one another in different time intervals. All these attributes affect the signal-to-interference-plus-noise ratio (SINR) at a receiver. Because the SINR is directly related to the data rate which a transmission can sustain, another PHY/MAC attribute that can be tuned to enhance the overall system performance is the data rate. Fig. 4 gives a taxonomy of MAC research issues in WMNs.

A. Spatial Reuse

Several interesting related research issues are – What is the relationship between the transmit power and the carrier sense threshold? Will tuning one parameter implies the other? What is the trade-off between (i) increasing the level of spatial reuse by using smaller power or larger carrier sense threshold and (ii) decreasing individual data rates each node can afford (because of the decrease in the SINR as a result of using smaller power/larger carrier sense threshold)? Specifically, when the transmit power decreases, the SINR decreases as a result of the smaller received signal [6, 7]. Similarly, when the carrier sense threshold increases, a node may determine the medium to be idle when some other concurrent transmissions are in progress. This leads to the increase in the interference level and the decrease in the SINR. In both cases, the receiver may not be able to correctly decode the signal and the data rate sustained by each transmission may decrease. Finally, what is the minimal information that needs to be exchanged among mesh nodes in order to realize a (sub-)optimal solution (if any)? Answers to these questions are important research issues in order to fully exploit spatial reuse.

B. Channel Assignment

Traditional multi-hop wireless networks are mostly comprised of single-radio nodes. Such networks may suffer from capacity degradation due to the half-duplex transmission capability of the wireless medium. A solution is thus to equip nodes with multiple radio interfaces and assigning orthogonal channels to radios. In this manner, nodes can communicate simultaneously with the minimal interference, although they are within the interference range of each other. Even in networks with only single-radio nodes, capacity improvement can be expected by enabling nodes with the interference range of each other to operate on different channels to minimize the amount of interference. Currently the IEEE 802.11b/g and IEEE 802.11a standards provide, respectively, 3 and 12 orthogonal channels which can be used simultaneously within a neighborhood. A simple design for multi-radio and multi-channel networks would be to equip each node with the same number of radios as the number of orthogonal channels. However, due to both the economical and technical reasons only a limited number of radios may be equipped at each node. The research issue is then how each node determines the channel on which each of its radios will operate, in order to reduce the interference caused by simultaneous transmissions on the same channel.

C. Rate Control

Rate control refers to the process of dynamically adapting the data rate according to the channel status, with the aim of choosing an optimal data rate for the given channel condition. An example is the auto-rate function available in most IEEE 802.11 a/b/g chipsets. There are 4 data rates (1, 2, 5.5, 11 Mb/s) available in 802.11b and 8 data rates (6, 9, 12, 18, 24, 36, 48, 54 Mb/s) available in 802.11 a/g. Usually the higher the SINR, the higher the data rate. For a given SINR, one may then choose the highest possible data rate (that allows correct decoding) in order to maximize the throughput. The procedure of rate control consists of two phases: channel estimation and rate selection. The major research issues to be considered are: (i) which metric should be used to measure the channel quality? and (ii) which design rule associated with the metric should be used to select a new data rate? Rate control algorithms have been studied quite extensively in [32]-[41]. As mentioned above, rate control aims to adjust the channel data rate with respect to the time-varying channel status.

D. Spatial-Temporal Diversity

There are, however, two issues that must be addressed in order to realize spatial diversity. First, the set of paths along which transmissions can take place with the least inter-flow interference must be identified, perhaps with received signal strength measurements. Second, based on the set of non-interfering paths, the order in which packets of different connections are scheduled to be transmitted must be determined, with the objective of mitigating interference. The problem of mitigating interference and improving network capacity was also considered from the angle of spatial-temporal diversity in [26].

E. Transmit Power Control

The issue of transmit power control has been extensively studied in the context of topology maintenance by graph-theoretic approaches [8]- [16], where the major objective is to reduce power consumption, mitigate MAC interference, while preserving network connectivity. Since the energy required for transmission increases with the distance (at least in the order of two), it makes sense from the perspective of energy saving to replace one long link with several short links. Furthermore, reducing the transmit power also mitigates MAC interference, which in turn improves the network capacity (as a result of less MAC-level collisions and retransmissions). However, the transmit power cannot be reduced to the extent that network connectivity is not preserved. Use of transmit power control for maximizing network capacity has been considered in [17] – [21].

F. Carrier Sense Adaptation

Recently a number of studies have focused on exploiting IEEE 802.11 physical carrier sense to increase the level of spatial reuse [22]-[25]. By physical carrier sense, it means that before attempting for transmission, a node senses the medium and defers its transmission if the channel is sensed busy, i.e., the strength of the received signal exceeds a certain threshold CS_{th}. Carrier sense reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe margin (termed as the carrier sense range) to engage in concurrent transmissions.

G. MAC Implementation

A MAC protocol can be implemented in two types of architecture. In the classical implementation architecture, a MAC protocol is implemented in software (MAC driver), firmware, and hardware. Usually, packet queuing, network formation, node association, and so on, are done in the driver. Timing critical functions, e.g., time slot generation, backoff procedures, etc., are performed in the firmware. The actual real-time operation of the MAC protocol is done in the hardware. For example, when a backoff counter is determined, the exact decrement of this counter is done in the hardware in order to achieve high accuracy. Thus far, many companies have tried to pull more functions in the firmware into the driver level so that the driver has more freedom to control/modify the MAC protocol. This type of method is usually called a "softMAC" implementation. However, since many key functions are still located in firmware, the timing critical part of the MAC protocol is hard to modify. This problem has been solved in the second implementation architecture, which is called software defined radio (SDR) MAC architecture. In this new architecture, no firmware is available. All timing critical functions are implemented in the hardware, but almost all of them can be controlled or modified by the driver. Thus, such an architecture provides a powerful approach to research and development of new MAC protocols.

IV. MAC PROTOCOLS FOR WMNS

The MAC protocols for WMNs can be classified into two categories: single-channel and multichannel MAC protocols.

A. *Single-Channel MAC Protocols*

Most of the existing MAC protocols are designed to be operated on a single channel. Table 1 compares some of the existing protocols based on whether they use directional transmissions or out-of-band tones, where ''D'' represents directional, ''O'' represents omnidirectional, and ''D/O'' means directional transmission and omni-directional receiving [46]. Even though most of the proposed protocols improve performance compared to the standard 802.11 MAC, supporting directional antennas in multihop WMNs is a difficult task and future work in this area is needed to fully exploit the benefits of beam-forming.

Table 1. Comparison of single-channel MAC protocols

Protocols	Carrier Sensing	RTS	CTS	DATA	ACK	Tones
Directional MAC (D-MAC) [42]	O^a	D/O^b	O/O	D/O	D/O	No
Tone-based Directional MAC (Tone DMAC) [43]	O	D/O	D/O	D/O	D/O	Yes
Directional Virtual Carrier Sensing (DVCS) [44]	D^c	D/D	D/D	D/D	D/D	No
Circular Directional RTS [45]	O	Circular-D/O	D/O	D/D	D/D	No

O^a: Omnidirectional
D/O^b: Directional transmission and omnidirectional receiving
D^c: Directional

B. *Multi-channel MAC Protocols*

The existing multichannel MAC protocols can be classified according to the channel selection techniques. Specifically, based on the way the channel is selected, existing approaches can be classified into three categories: (1) handshake-based channel selection, (2) channel hopping, and (3) cross-layer channel assignment. Existing schemes can also be classified based on other criteria. For instance, some protocols use a common control channel for all nodes, while others do not. The purpose of using a common control channel is to transmit control packets that assign data channels to mobile nodes. Some protocols require multiple transceivers, while others require only one transmitter and multiple receivers, or one transceiver. Multi-channel MAC protocols are studied in [27] – [31].

Many multichannel MAC protocols utilize a handshake between the transmitter and the receiver for channel selection. Examples include the dynamic channel assignment (DCA) protocol [47], the multichannel CSMA MAC [48], and multichannel MAC (MMAC) [27]. Just like the IEEE 802.11 standard, the handshake mechanism is realized by exchanging control messages between senders and receivers.

Some MMAC protocols use channel hopping to achieve data exchange between two nodes. Two such examples are receiver-initiated channel-hop with dual polling (RICH-DP) [49] and slotted seeded channel hopping (SSCH) [31].

Distributed channel assignment problems have been proven to be NP-complete and are thus computationally intractable [50,51]. There exist only a few heuristic solutions, all with considerable complexity, especially for the mobile environment [50,51,52]. However, one way to achieve effective channel selection with little control overhead is by combining channel assignment with the routing protocol [53]. Because the channel assignment is performed by routing, the MAC protocol only needs to manage MAC. As a result, the design of MAC protocol is significantly simplified. A second advantage of this approach, i.e., the separation of channel assignment and MAC, is that it enables optimization of different modules separately. For instance, channel assignment can be combined with different reactive or pro-active routing protocols. The MAC protocol can also be designed independently without the knowledge of how channels are assigned to individual nodes. In addition, the separation of functions makes it possible to design backward compatible and practical MMAC protocols. MMAC protocol is based on the idea of cross-layer channel assignment [53].

Table 2. Comparison of Multi-channel MAC protocols

Protocols	Medium Access	Channel Selection	Hardware Requirement
Dynamic Channel Assignment (DCA) [47]	CSMA/CA	Per packet	2 Transceivers
Multichannel MAC (MMAC) [53]	CSMA/CA	Per-route setup	1 or 2 Transceivers
Multichannel MAC (MMAC) [27]	CSMA/CA	Per beacon interval	1 Transceiver synchronization required
Multichannel CSMA [48]	CSMA/CA	Per packet	1 Transmitter multiple receivers
RICH-DP [49]	Channel hopping	Hopping sequence	1 Transceiver synchronization required
SSCH [31]	Channel hopping	Hopping sequence	1 Transceiver synchronization required

In addition to utilizing different channel selection techniques, existing MMAC protocols have different MAC techniques and hardware requirements. Table 2 summarizes some important features of existing MMAC protocols. There is no general rule as to which scheme is better than another. Simpler schemes with reduced hardware requirements are easy to implement, whereas complex schemes with greater hardware requirements often yield better performance.

V. Conclusions And Future Work

Even though wireless MAC protocols have been extensively studied since the 1970s, advanced MAC protocols suitable for WMNs did not gain much attention until recently. Such MAC design, however, is a challenging task due to the ad hoc nature of WMNs. In this paper, we presented the design objectives and technical challenges for effective MAC protocols in WMNs and we reviewed existing MAC protocols. We have presented several research issues pertinent to the performance and capacity optimization issues in WMNs.

Due to the multihop and ad hoc nature of WMNs, supporting directional antennas is not an easy task and most existing designs tend to be complex. In the future, simple and more efficient MAC protocols may be built assuming a simplified mesh architecture or multiradio support at each node. Another important future direction is the capacity of wireless networks that utilize directional antennas or multiple channels. When advanced techniques such as MIMO and cognitive radios are used in the physical layer, novel MAC protocols considering MAC/physical cross-layer design need to be proposed to utilize the agility provided by the physical layer.

Some mesh routers in WMNs are responsible for the integration of various wireless technologies. Thus, advanced bridging functions must be developed in the MAC layer so that different wireless radios such as IEEE 802.11, 802.16, 802.15, etc., can work seamlessly together. Reconfigurable/software radios and the related radio resource management schemes may be the ultimate solution to these bridging functions. Most of the existing research efforts in MAC are focused on capacity, throughput, or 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. Reconfigurable MAC enables the freedom of new inventions added to the MAC protocol and the cross-layer design between MAC and other protocol layers such as physical and routing. However, the challenge is that usually both software and firmware are involved in MAC protocol implementation. A promising trend in MAC chipset design is that the architecture becomes more and more reconfigurable. When software radios become mature enough for commercial use, more flexible and powerful MAC protocols can be easily developed.

In WMN, because of the special network architecture, it is quite a challenge to manage MAC process for mesh clients and mesh routers. To avoid packet collisions among contending terminals, not only data payload, but also control messages should be protected against packet collisions as far as possible. Energy conservation capability is preferred by any mesh client related communications. Power aware, interference aware, and rate adaptive capabilities are usually considered at the same time by combining the MAC layer and physical layer characteristics together. To achieve high rate, energy saving and collision free transmissions, a number of open issues specified in this paper should be addressed.

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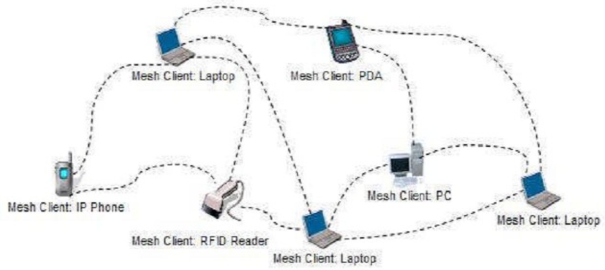

Fig. 1. Client Architecture

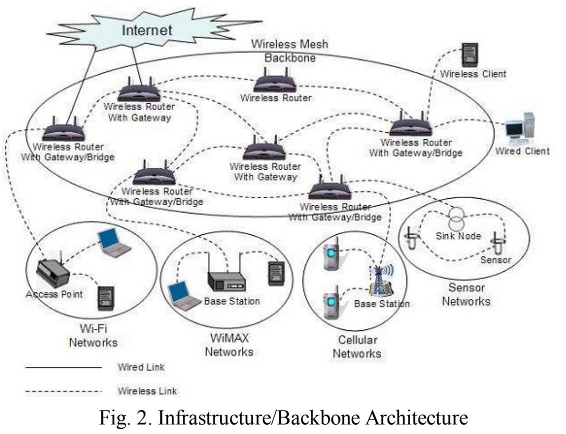

Fig. 2. Infrastructure/Backbone Architecture

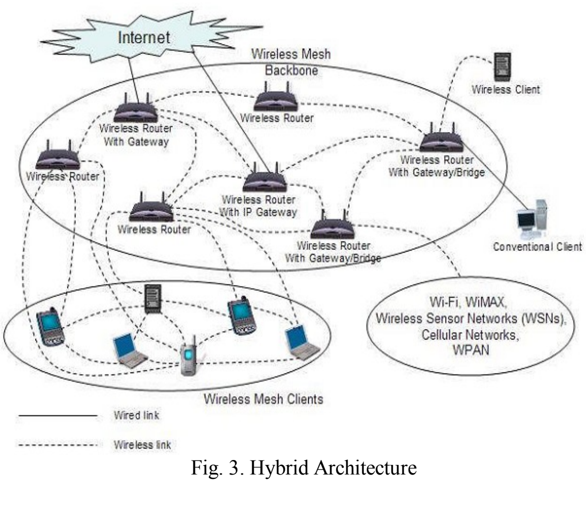

Fig. 3. Hybrid Architecture

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