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Distributed medium access control for wireless mesh networks

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Summary

Wireless mesh networking is an emerging technology for future broadband wireless access. The ad hoc manner of wireless mesh networks (WMNs) determines that distributed medium access control (MAC) protocols are desired. Multimedia traffic with heterogeneous quality of service (QoS) requirements is expected to be supported in small-, medium-, and large-scale WMNs. Wireless mesh routers in WMNs are located in fixed sites with low (or no) mobility and no power constraints, thus comprising a robust and reliable wireless mesh backbone. Different networking characteristics between the mesh backbone and various mesh client networks give rise to the demand of heterogeneous MAC design. Due to new design purposes and new networking structures, existing MAC protocols designed for mobile ad hoc networks may not be effective or efficient for multi-purpose WMNs. This paper provides an overview of distributed MAC protocols based on their underlying design objectives and methodology, discusses their features and suitability for WMNs, and identifies potential challenges and open research issues. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: wireless mesh networks (WMNs); medium access control (MAC); quality of service (QoS); priority; resource reservation; fairness; multi-channel; cross-layer design

1. Introduction

The wireless mesh networking has emerged as a promising technology for future broadband wireless access [1,2]. Although the notion of mesh networking has been discussed extensively in wireline and optical networks [3,4], the research mainly focuses on restoration of link failure and/or design of survivable and healing networks. When applying mesh networking techniques over shared wireless medium with limited radio spectrum, many new challenges are raised such as fading mitigation, effective and efficient medium access control (MAC), quality of service (QoS) routing, call admission control etc. Recently, the wireless mesh networking has been attracting more and more attentions from academia and industry.

Wireless mesh networks (WMNs) consist of wireline gateways, mesh routers, and mesh clients, organized in a three-tier architecture [1,5], as shown in Figure 1. A mesh client network can be formed in

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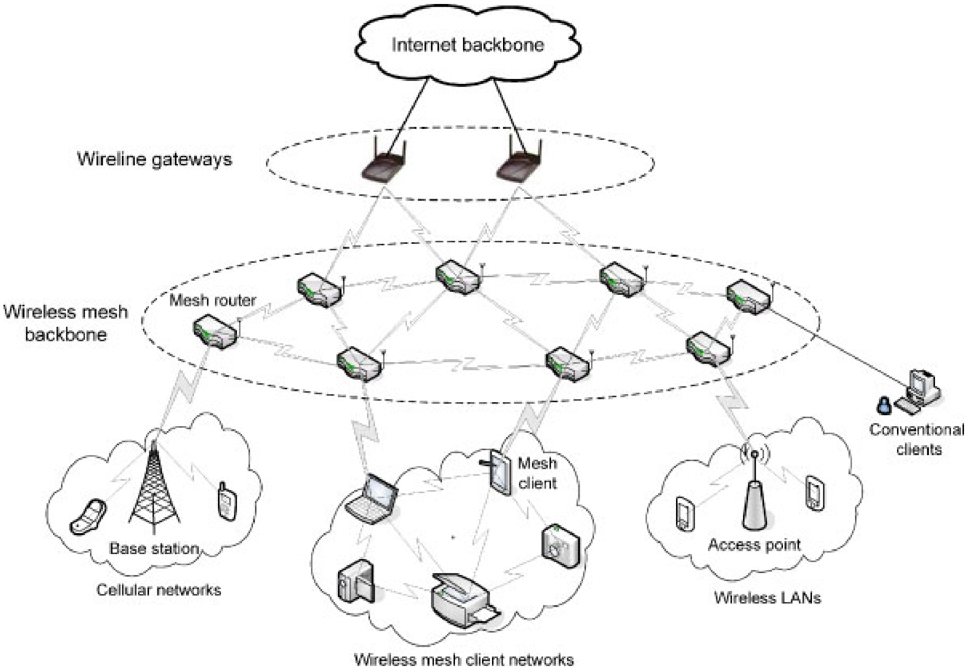

Fig. 1. An illustration of wireless mesh networks.

an ad hoc manner, and connected to one or more mesh routers. The mesh routers in fixed sites comprise a wireless mesh backbone to provide relay service to the mesh client networks and other access networks such as cellular networks, wireless local area networks (LANs) etc. The wireless mesh backbone provides a platform to integrate the wireless access networks, so that a multi-mode mobile station with multiple air interfaces can roam freely among the access networks and select desired services. The addition of wireless mesh backbone between the Internet backbone and access networks can facilitate the *loose coupling* in the interworking of heterogeneous wireless access networks, as the mobility signaling can traverse a relatively short path [6]. The wireline gateways are to connect the wireless mesh backbone to the Internet backbone. One prominent attraction of this architecture stems from large-scale deployment, dynamic self-configuration, and self-management with high-link reliability [1]. In addition, to support fast handoff, micro-mobility protocols such as cellular IP [7] and HAWAII [8] can be incorporated smoothly in the three-tier architecture [9].

WMNs can be deployed in various practical scenarios with different purposes, thus referred to as *multi-purpose WMNs*. In a small-scale network such as in home networking, the coverage of wireless accessibility of different devices can be enlarged by the mesh connectivity established among mesh routers. Thus, dead zones are minimized. In a medium-scale network such as in office networking, deployment of WMNs is relatively simpler and more economical by replacing the bulky cables. By efficient and distributed wireless transmissions, a bottleneck at the central switch and/or the end router can be avoided. Thus, applications such as videoconferencing can be served smoothly. In a large-scale network such as in city networking, the advantages of WMNs are more obvious. The data rate in WMNs is generally higher than that in cellular networks, thus supporting more users and increasing the system capacity. Peer-to-peer transmissions within the network do not need to involve the conventional wireline Internet backbone. Most importantly, the setup cost and the maintenance cost can be significantly reduced as complicated and time-consuming setup procedures such as land construction and deployment of underground cables are no longer necessary. Furthermore, with application-specific MAC protocols, WMNs are very promising in tsunami/earthquake reporting and other emergency networking [1]. People nearby can be informed promptly. Therefore, WMNs will play an important role in supporting different applications, ranging from small-scale networking to large-scale networking in different application-specific circumstances.

For WMNs, due to the limited radio bandwidth, MAC is essential to coordinate the transmissions from/to the mesh routers and clients in an effec-

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tive and efficient manner. MAC for wireless networks can be categorized into two groups: centralized MAC and distributed MAC, according to whether the access to the medium is coordinated in a centralized or distributed manner. Centralized MAC is usually designed for infrastructure-based networks such as cellular networks, benefiting from the large processing power and global information at the central controller. The central controller collects traffic and/or channel information from all the mobile nodes, determines the resource allocation to all the nodes by polling, reservation, or demand assignment, and informs the nodes of the resource allocation decision. On the other hand, distributed MAC is suitable for infrastructure-less networks such as mobile ad hoc networks without a pre-existing central controller, where each node determines its own access to the medium according to its local observation of the channel [10]. Due to the self-organization nature of WMNs, it is desired to apply distributed MAC to achieve efficient resource utilization.

Without central coordination, distributed MAC is more challenging than centralized MAC as contention and hence transmission collision are generally inevitable. There are extensive research results on distributed MAC over mobile ad hoc networks in the literature [11–15]. Although organized in an ad hoc manner, the WMNs are quite different from traditional mobile ad hoc networks, as explained in the following. First, multimedia traffic with heterogeneous QoS requirements is expected to be supported in small, medium, and large WMNs. Second, the wireless mesh backbone is with low (or no) mobility and has no power constraint, and the wireless clients may form a network attached to fixed mesh routers, thus with only limited mobility. Third, the different networking characteristics between the wireless mesh backbone and the mesh client networks determine that heterogeneous MAC should be applied. Fourth, the traffic volume in the wireless mesh backbone in a large-scale WMN can be very large and can vary from one mesh router to another, thus posing significant challenges on the MAC design. Therefore, it may not be effective or efficient to directly apply existing MAC protocols proposed for ad hoc networks to the wireless mesh backbone and the mesh client networks. There are many open issues to improve and enhance WMN MAC, taking into account the unique WMN characteristics. This paper is to provide a comprehensive overview on distributed MAC protocols based on their design objectives and methodology, discuss their suitability for WMNs, and present potential challenges and further research issues in this area. The rest of the paper is organized as follows. The design criteria and classification of distributed MAC protocols for WMNs are given in Section 2. From Section 3 to Section 8, various distributed MAC protocols are presented according to their underlying design purposes and techniques. In Section 9, potential challenges and open research issues are discussed. Finally, the conclusion remarks are given in Section 10.

2. Design Criteria and Classification of Distributed MAC

MAC is crucial in wireless communications, which defines the way how wireless nodes contend and share the scarce radio resources. Generally, it is impossible for a wireless node to transmit and receive at the same time over the same bandwidth, and hence collision is hard to detect during transmission. Simultaneous transmissions of hidden terminals can cause a collision at the common receiver. In addition, the exposed terminal problem can reduce the system utilization. Therefore, a primary goal of MAC protocols for WMNs is to avoid collisions and allow simultaneous transmissions whenever possible.

WMNs are expected to support wireless multimedia communications for future broadband Internet access. One major challenge in distributed MAC is QoS provisioning with efficient resource utilization. In the shared wireless medium, simultaneous transmissions of different nodes may result in collisions so that retransmissions are needed, which may increase transmission delay or cause packet loss. Therefore, MAC protocols should be designed to facilitate successful transmissions by defining rules to ensure efficient, orderly, and fair communications among all the nodes. Due to heterogeneous traffic types in a network (e.g., real-time traffic and non-real-time traffic), different QoS guarantees are required such as delay constraints for voice and video applications, and throughput guarantee for delay-insensitive data applications. Hence, MAC protocols should be adaptive to various traffic types. Common performance metrics in MAC design include throughput, delay, fairness, multimedia support, and robustness to link vulnerability [10,16].

One minimal requirement of WMN MAC is to support best-effort services. Throughput is the main design objective. The major task is to alleviate the hidden terminal and exposed terminal problems, to be discussed in Section 3. On the other hand, QoS support is desired in distributed WMN MAC by means of: (1) priority mechanisms, to assign high priority in the contention to

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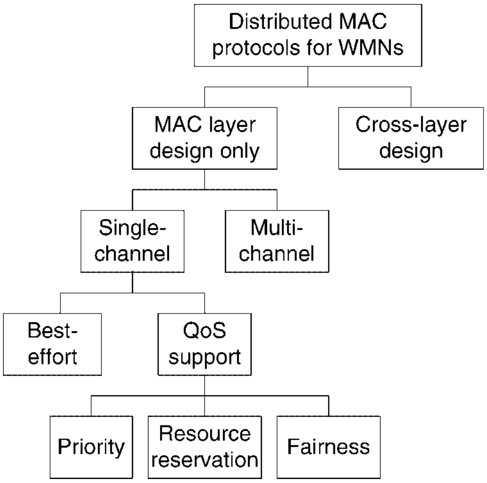

Fig. 2. The MAC protocol classification.

more important traffic such as voice or video, to be discussed in Section 4; (2) resource reservation, to allow a node to transmit without collision after a successful reservation, to be discussed in Section 5; and (3) fairness enhancement, to provide a fair share of the wireless medium access, to be discussed in Section 6. Further, most of the distributed MAC protocols are mainly designed for a *single-channel* scenario, where a single data channel is used by all the nodes, and two nearby transmissions may lead to a collision. On the contrary, if the wireless communications are supported by spread spectrum technology such as code division multiple access (CDMA) or ultra-wideband (UWB) transmission, simultaneous transmissions spread by different codes will not collide, but generate interference to each other. The distributed MAC design in such a *multi-channel* scenario is investigated in Section 7. In addition, for multimedia traffic over WMNs with broadband Internet access, MAC layer design independent of other layers may lose some flexibility or efficiency. Cross-layer design approaches have shown the potential to benefit from information exchanges among different protocol layers, to be discussed in Section 8. As a summary, Figure 2 gives classification of the distributed MAC protocols discussed in this paper.

3. Best-Effort Service Support

Due to the lack of a centralized controller, many best-effort distributed MAC schemes such as random access have been proposed with no QoS guarantee. This is the first step for distributed resource allocation, though only best-effort services are supported. ALOHA [17] is the first random access protocol proposed for packet radio networks. A node transmits when it has traffic to send. If a collision occurs, the node retries after a random period. The maximum throughput is quite low. By reducing the vulnerable period by half, slotted ALOHA results in a better throughput. To reduce the collisions in ALOHA, a mechanism named carrier sense multiple access (CSMA) is introduced, in which a node senses the channel before transmission and defers the transmission if the channel is sensed busy. However, when CSMA is applied over multi-hop networks such as the wireless mesh backbone and mesh client networks, the hidden terminal and exposed terminal problems [10,16,18] will degrade the system performance. To improve throughput, request-to-send (RTS)/clear-to-send (CTS) dialogue, or a combination of RTS/CTS dialogue and carrier sensing can be employed. The RTS/CTS dialogue is used before the DATA frame (i.e., the information frame) exchanges. A sender first sends an RTS frame to a receiver. Upon successful reception of the RTS, the receiver replies with a CTS. All neighbors hearing RTS or CTS defer their transmissions. Thus, hidden and exposed terminal problems can be alleviated. Based on these mechanisms, many well-known protocols have been proposed, such as multiple access with collision avoidance (MACA) [19], MACAW [20], floor acquisition multiple access (FAMA) [21], CSMA with collision avoidance (CSMA/CA) [11,22]. Receiver initiated collision avoidance schemes are also proposed, such as MACA by invitation (MACA-BI) [23] and the receiver-initiated multiple access with simple polling (RIMA-SP) [24]. All the schemes can be applied over WMNs. On the other hand, another popular type of collision avoidance schemes, based on busy tones, is particularly suitable for mesh routers with no power constraints because the power consumption by busy tones is not a problem anymore, as discussed in Subsection 3.1. In addition, some contention-aware MAC protocols are effective to improve the system throughput performance, particularly useful for WMNs, which are characterized by low (or no) mobility of mesh routers, and limited mobility of mesh clients, as discussed in Subsection 3.2.

3.1. Busy-Tone Aided Multiple Access

Separation of control channel and information channel is a popular way to increase system throughput. Busy tone multiple access (BTMA) [18] is one example, in which collision avoidance can be done by using out-of-band signaling. In BTMA, a node broadcasts an out-of-band busy tone when sensing a busy medium. Any node

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hearing a busy tone does not initiate a transmission, so as to prevent hidden terminals from transmitting simultaneously. In receiver-initiated busy tone multiple access (RI-BTMA) [25], the receiver broadcasts the busy tone during the process of reception. Hence, the busy tone not only acknowledges the sender's transmission but also prevents other nodes from transmission, by alleviating the hidden terminal and exposed terminal problems. One limitation is the dependence on slot synchronization [12], which is difficult to achieve in distributed WMNs.

Two busy tones are used in dual busy tone multiple access (DBTMA) [12]. One (called the receive busy tone, $\mathrm{BT_r}$) is broadcast by a receiver during DATA reception, and the other busy tone (called the transmit busy tone, $\mathrm{BT_t}$) is used to protect an RTS frame, which further reduces the number of collisions. For nodes in the vicinities of the sender and the receiver of interest, any sensed busy tone refrains them from starting transmission of RTS frames. It has been shown that DBTMA prevails over RI-BTMA by a performance gain of 20%. One drawback is that the busy tone generation and detection may take some time, which results in a longer vulnerable period to collisions. Nonetheless, this type of best-effort-based MAC protocols improves the system performance at the expense of the increased hardware circuitry design.

BTMA does not address the RTS collisions due to hidden terminals. The case is even worse in a crowded WMN. An effective solution is to make the carrier sensing range of the $\mathrm{BT_t}$ channel twice the transmission range of the information channel, so that the $\mathrm{BT_t}$ busy tone can be sensed by all hidden terminals in the traditional MAC. Thus, RTS collisions can be avoided: when a node is sending RTS, all two-hop neighbors can sense the $\mathrm{BT_t}$ busy tone and defer their transmissions [26]. A similar idea is presented in Reference [27] where no busy tone is used. It is shown that when the carrier sensing range (of the information channel) is larger than two times of the transmission range (of the information channel), system performance can still sustain without the need of RTS/CTS handshaking.

One argument against busy-tone aided MAC is the extra power consumption by busy tones. However, for the mesh routers at fixed sites with no power constraints, the concern of power consumption can be neglected.

3.2. Contention-Aware MAC

For WMNs with low mobility, it is possible that a node has the knowledge of its neighborhood. This property can facilitate contention-aware MAC design.

Benefiting from the neighborhood information, a node can adopt the SEEDEX protocol [28] to avoid collision. SEEDEX employs the exchange of seeds of a pseudo-random number generator. All nodes broadcast their schedules to their two-hop neighboring nodes. Then, a transmission may be initiated if the sender is in the PT (i.e., 'possibly transmit') state, and the intended receiver and its one-hop neighbors are in the L (i.e., 'silent') state simultaneously. The sender will wait some time for an ACK or NACK after its transmission. Knowing the schedules of nodes in the vicinity of the receiver helps to solve the hidden terminal problem. In addition, the main advantage of SEEDEX is to exchange transmission schedules simply by exchanging seeds, thereby requiring only limited overhead. The seed exchange is performed periodically so as to deal with the possible node mobility and the change of network topology. Although the performance depends on the pseudo-random number generator, the scheme brings some insights of how to design an MAC protocol for distributed WMNs to reduce collisions.

Adjusting the transmission probability based on the channel utilization is another way to help avoid collisions. A distributed contention control mechanism for power saving (PS-DCC) [29] makes use of an estimate of slot utilization to update a transmission probability of a node. Although no QoS support is provided, the concept of dynamic MAC adaptation using local information such as the number of retransmissions is prominent, especially in fully distributed WMNs without central coordination. On the other hand, channel-aware schemes operated locally may lead to unfairness and instability of the system. To address these issues, the existence of some stable operational points such as Nash equilibrium [30] is desirable in a network in which each node updates its contention and transmission strategy in a distributed manner.

In addition, for the wireless mesh backbone, each wireless router can know the number of its neighboring routers. Based on this information, the contention behavior of the MAC can be dynamically tuned so as to achieve a theoretical throughput limit [31].

In summary, best-effort-based MAC protocols aim at increasing system throughput by solving the hidden terminal and exposed terminal problems. They may be effective to handle homogeneous traffic in a flat network topology. However, simply employing these protocols in multi-purpose WMNs can cause performance degradation. Though the preceding schemes can only provide best-effort services for data transmission, some

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design principles are the stepping-stones for designing advanced MAC protocols which guarantee QoS requirements. To deal with different types of multimedia traffic flows, prioritization may be needed.

4. Priority

With an integration of more than one type of traffic, best-effort MAC is no longer desirable due to the lack of service differentiation. For wireless mesh networks supporting multimedia traffic, service prioritization plays an important role in providing a certain degree of QoS requirements. Priority can be provided to important traffic types. For example, delay-sensitive traffic such as voice may need to have a higher priority than the traffic such as data. Urgent messages of some scenarios should be transmitted immediately. Some subscribers may not be satisfied by connection only, and may be willing to pay more for better than best-effort services. Generally, priority in distributed MAC can be achieved by various ways: differentiated contention window size (CW) and/or inter-frame space (IFS), differentiated frame length, jamming, and out-of-band signaling, as elaborated in the following.

4.1. Differentiated CW and/or IFS

When the access to the channel is controlled by a backoff procedure, service differentiation can be achieved by adjusting the backoff algorithm [32]. The mandatory distribution coordination function (DCF) in IEEE 802.11 [11] only provides best-effort services. As an extension of DCF, the enhanced distributed channel access (EDCA) [33] in IEEE 802.11e is proposed in order to provide relative priority. Different traffic flows are put into different queues or access categories (ACs). A higher-priority AC is assigned smaller initial contention window ($\mathrm{CW}_{\mathrm{min}}$) and maximum contention window ($\mathrm{CW}_{\mathrm{max}}$), and shorter arbitration IFS (AIFS), thus gaining an advantageous position in the contention. EDCA has two main drawbacks [15]. First, only statistical priority is provided. The backoff timer of each AC will count down whenever the channel is sensed idle for a duration more than the AC AIFS. Thus, it is still possible that the backoff timer for a low-priority packet will reduce to a very small value (shorter than any backlogged high-priority packet). In this case without preemption, the low-priority packet can access the channel in the presence of high-priority packets, which is not desirable. Second, EDCA may lose its effectiveness when applied to multi-hop networks with hidden terminals, such as in WMNs, to be discussed in Subsection 4.4.

4.2. Frame Length Differentiation

In addition to the modification of the CW and the IFS, prioritization can be achieved by frame length differentiation [34]. Nodes with higher priority can send longer frames while those with lower priority can only send shorter frames. It provides a simple way to offer service differentiation, though the chance of successful transmission for all frames is the same under the same contention mechanism. Further, this scheme may not be effective for real-time traffic because the MAC layer frame size of real-time traffic is largely dependent on the source coding rate and packetization procedure from the application layer to the Internet protocol (IP) layer.

4.3. Differentiation via Jamming

EDCA can only provide statistical priority. Thus, the performance of high-priority traffic may be degraded if the traffic load of lower-priority traffic is high, which may not be desired. To provide absolute priority, the Black-Burst (BB) contention scheme [35] is effective to separate high-priority nodes with real-time traffic from low-priority nodes in a single-hop network. The main goal is to minimize the delay of real-time traffic (the high-priority traffic). After sensing an idle channel for some time, the node with real-time traffic sends a BB signal (i.e., pulses of energy) to jam the channel. The length of the BB signal is an increasing function of the contention delay experienced by the sender. If a node senses the channel busy after the completion of its BB transmission, it will defer. Thus, the sender with the longest BB signal (i.e., longest experienced delay) wins and can access the medium. Lower-priority nodes use the ordinary CSMA/CA to contend after higher-priority nodes' transmissions are completed. The strengths of this mechanism are: (1) the delay of real-time traffic is minimized; and (2) prioritization is provided among real-time flows which experience different delays.

Via the similar principle of BB contention, the priority can be achieved in the following way [36]. Consider a network with several service classes with class IDs from 1 to K. Class 1 is the most important class, and class K is the least. Each class is assigned a BB length BB_i, where $\mathrm{BB}_1 > \mathrm{BB}_2 > \cdots > \mathrm{BB}_K$. When the channel has been sensed idle for a distributed IFS (DIFS) period, a node with traffic class i sends a BB

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with length BB_i. Among all the contending nodes, stations with the highest priority will send the longest BB and continue the contention, while other stations lose the contention.

The BB contention can also be applied effectively with minor modification to the EDCA [13]. Again, consider K service classes. Class i ($1 \le i \le K$) is assigned an AIFS value AIFS[i], where $\mathrm{AIFS}[1] < \mathrm{AIFS}[2] < \cdots < \mathrm{AIFS}[K]$. For a node with traffic class i, after the channel has been sensed idle for a duration AIFS[i], it sends a BB with length (in the unit of slot time) equal to its backoff timer. Thus, as long as there exists a node with higher-priority traffic, the nodes with lower-priority traffic (say class j) sense the busy medium and will not start the contention because the channel idle duration is less than their AIFS[j]. Thus, only the backlogged nodes with the highest priority try to access the channel. It can be seen that the priority is guaranteed by the different starting points of BB signals sent by different traffic classes.

One concern about implementation of the BB contention is that BB signals may cause a waste of energy. For the wireless mesh backbone without power constraints, BB contention can be an effective solution. However, the BB contention does not deal with the hidden terminal problem. Thus, it is still possible that a high-priority flow may lose its advantages over a low-priority flow in a multi-hop WMN.

4.4. Differentiation by Out-of-Band Signaling

The priority mechanisms discussed in the above may lose their effectiveness in a multi-hop environment. To manage multi-hop distributed networks, busy tone priority scheduling (BTPS) [15] can be used. Consider the example in Figure 3, where there is a high-priority flow from A to B, and a low-priority flow from C to D. A dashed circle means the transmission and sensing ranges of the node in the circle center. When DCF or EDCA is applied, the high-priority flow will be starved because of the hidden terminal C. To address this problem, BTPS uses two narrowband busy-tone signals (BT_1 and BT_2). Whenever node A has a high-priority packet backlogged, it will broadcast a BT_1 during the carrier sensing period. Node B will broadcast a BT_2 after hearing the BT_1. All low-priority nodes hearing either BT_1 or BT_2 will defer their transmissions for some time. Hence, whenever node A has a high-priority packet backlogged, node C will notice it and defer its transmission, thereby ensuring channel access priority of node A. The hidden terminal problem is solved. The advantage of BTPS is that it ensures priority access of high-priority packets in a multi-hop networks. Furthermore, in the absence of high-priority flows, low-priority flows can achieve good throughput performance without being forced to wait for a long IFS. However, it can only classify the traffic into two categories: high and low priorities, which may not be applicable to WMNs having more than two service classes.

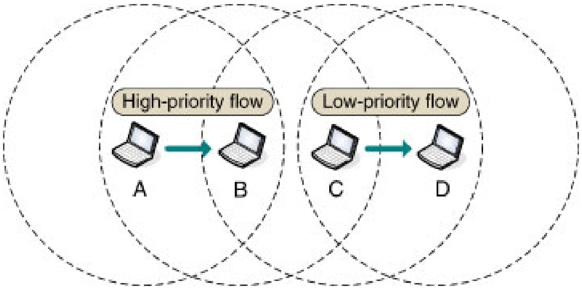

Fig. 3. Priority in a multi-hop network.

In summary, regarding the overall system performance, priority-based MAC protocols are better than best-effort-based MAC protocols in networks with heterogeneous traffic. The target of service differentiation provisioning can be met by modification of system parameters and/or extra signaling. With service differentiation, higher-priority packets can occupy more channel resources and have higher chances to win the contention. Without doubt, it is very crucial in many cases of WMNs to allow urgent packets to be transmitted first. For example, in a disaster such as tsunami, the emergency signals must be sent out immediately to inform people nearby. Generally, a coarse-grain QoS level can be achieved by priority-based MAC protocols. In order to achieve fine-grain QoS guarantee (e.g., contention-free transmission, delay bound guarantee for real-time traffic, and throughput guarantee for data traffic), resource reservation is a better choice.

5. Resource Reservation

To provision fine-grain QoS to heterogeneous traffic, resource reservation is generally required. By reserving a certain amount of channel resources, some traffic flows can be transmitted without any contention. For example, in general, voice packets are generated periodically and have stringent delay constraints. Without frame or slot reservation, every voice packet has to contend with other packets in the shared medium where collisions are unavoidable. A delay bound is difficult to guarantee, and packet dropping is possible, thus users are not satisfied. On the other hand, resource reservation allows packet transmission without

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contention, thereby supporting certain QoS of multimedia traffic.

5.1. Reservation by Contention

Traditionally, reservation is made by contention, that is, each node contends to send a reservation request. If the request is acknowledged, the sender can send its frames without collision. In an integration of voice and data traffic, as periodic voice packets have delay constraints, they are usually treated as higher-priority packets. As an extension of packet reservation multiple access (PRMA) [37], the distributed PRMA (D-PRMA) [14] can achieve reservation in ad hoc networks. Once a voice node wins the contention of a slot, that slot is reserved for this voice node and the subsequent voice packets can be transmitted using this reserved slot without contention. There is no reservation for a data packet. The frame structure is shown in Figure 4. The time is partitioned into fixed-size frames, and each frame consists of *m* slots. Each slot is composed of *n* minislots, and two control fields can be included in each minislot: RTS/BI (busy indication) and CTS/BI. A voice node sends an RTS to its intended receiver through the RTS/BI of a minislot. If the receiver successfully receives this RTS, it replies with a CTS through the CTS/BI of the same minislot. All nodes hearing the CTS are not allowed to transmit during the remaining period of the same slot to avoid the hidden terminal problem. And, this slot is reserved for that voice sender. For distributed networks, at the first minislot of the reserved slot in each of the following frames, the receiver will send a BI through the RTS/BI field, and similarly the sender transmits a BI through the CTS/BI field. All nodes hearing a BI signal will refrain from the contention, thereby eliminating hidden terminals. If the node finishes its transmission, it simply stops sending the BI signal. The key advantage is that resource reservation is made without relying on the coordination of a central controller. Also, this scheme is fully distributed by taking into account the hidden node problem. One drawback is the need of global synchronization. Yet, resource reservation by random contention is feasible and applicable to WMNs to support different QoS requirements.

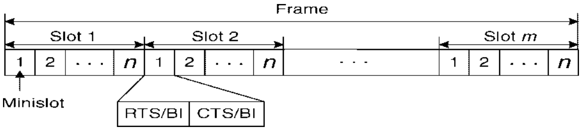

Fig. 4. The frame structure implemented in D-PRMA.

Similar to D-PRMA, a distributed MAC protocol for ad hoc wireless ATM multi-hop (AWAM) networks [38] is also effective for WMNs. In this multiple access scheme, a node contends for the access channel (ACH) and then starts a transmission in one of the available traffic channels (TCH) after the signaling packet from the intended receiver is successfully received. The channel is then reserved for subsequent packet transmission. Moreover, the access priority and the backoff algorithm of each node are dynamically adjusted according to its delay constraint in a distributed manner. With the adaptation of system parameters, prioritization is further provided among real-time flows with different delay requirements. This scheme also supports variable bit-rate real-time traffic. Combining resource reservation with traffic prioritization can further cope with different QoS requirements in a fully distributed fashion.

To further improve system performance, especially when voice traffic load is not high compared with data traffic, slots should not be only reserved for voice packets but also for data packets. In soft reservation multiple access with priority assignment (SRMA/PA) [39], both voice and data traffic can be transmitted without contention after winning the reservation. In particular, one special feature is the soft reservation implemented in this scheme, in which a voice node can snatch the slot already reserved by a data node when the access priority of the former is higher than that of the latter. The access priorities of voice and data packets are updated depending on the residual time of voice services and the queue length of data services, respectively, in a distributed and dynamic way. It is shown that the soft reservation increases channel utilization and reduces delay. This feature is quite useful for WMNs, in order to satisfy QoS requirements of real-time traffic and non-real-time traffic, and attain high-resource utilization.

Recently, IEEE 802.16 [40] has been standardized, which supports mesh connectivity in a distributed manner, and can be implemented in WMNs. In the MAC protocol, the resource reservation is managed by distributed scheduling. Similar to SEEDEX [28], one feature of the contention in this protocol is the pseudo-random election algorithm based on the transmission schedules of two-hop neighbors. A frame in the IEEE 802.16 mesh mode consists of a control subframe and a data subframe. The contention only happens in the control subframe. Similar to some other reservation-based schemes, once a node wins the contention based on the three-way handshaking Request-Grant-Confirm [40], the node can reserve multiple minislots in the data

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subframe for the subsequent packet transmissions. The scheduling message called MSH-DSCH is broadcast along with the three-way handshaking procedure and every node can then have the scheduling information in its two-hop neighborhood. The performance of IEEE 802.16 is strongly affected by the total node number, holdoff exponent value, and network topology [41]. Further investigation on the optimal settings of those parameters is needed.

5.2. Cluster-Based Reservation

For WMNs, an adaptive clustering algorithm [42] can generate non-overlapping and small clusters. In such a small cluster where each node is at most two-hop from other nodes, no cluster head is needed as each node can have the complete cluster information. Therefore, inside a cluster, scheduling is possible and resources can then be reserved and shared in a time-division multiple access (TDMA) manner. Problems of the bottleneck and the single-node-failure can be alleviated. By CDMA, two adjacent clusters are able to choose two distinct transmission codes to prevent inter-cluster collision. However, channel resources are wasted when traffic load is low. Inter-cluster interference and hence call admission control should be investigated carefully, using similar principles given in Subsection 7.2. This scheme may be applied to the wireless mesh backbone as its network topology is basically fixed. However, unless the network size is small, it is difficult to manage clusters in a fully distributed manner to cope with issues such as intra-cluster slot synchronization and delay constraints of some traffic flows.

5.3. Reservation with Priority

For WMNs with real-time and non-real-time traffic, it is desired that real-time traffic is assigned priority in resource reservation. Some priority mechanisms discussed in Section 4 can be used in the contention stage of the reservation. In addition, the distributed bandwidth allocation/sharing/extension (DBASE) [43] can be applied to support multimedia traffic. The dynamics of this scheme are shown in Figure 5. The short IFS (SIFS) is used by control frames such as CTS and ACK. The DIFS and priority IFS (PrIFS) are used by non-real-time and real-time traffic, respectively. The contention window of real-time traffic is set in a way such that a node with real-time traffic contends in the real-time contention period. By separating the real-time and non-real-time contention periods, real-time traffic can gain guaranteed priority over non-real-time traffic in the contention. In DBASE, each node maintains a reservation table (RSVT), which contains access sequence, MAC address, service type and required bandwidth corresponding to nodes that achieve reservation successfully. A real-time node that successfully obtains the channel will join the RSVT and it does not need to contend for the medium further throughout the whole session. The support of variable bit rate real-time traffic can be achieved by dynamically allocating the bandwidth on demand. However, the main drawback is that the original DBASE scheme is not designed for multi-hop distributed networks as the hidden terminal problem exists. Also, the real-time contention window size should be carefully selected. If the window size is too large, low-priority nodes have to wait for a long time before accessing to the channel, thereby underutilizing the resources. On the other hand, if the real-time contention window is too small, some real-time traffic flows may experience many collisions, which in turn wastes the system bandwidth. To address these problems, the BB contention can help to guarantee priority of real-time traffic in reservation [44].

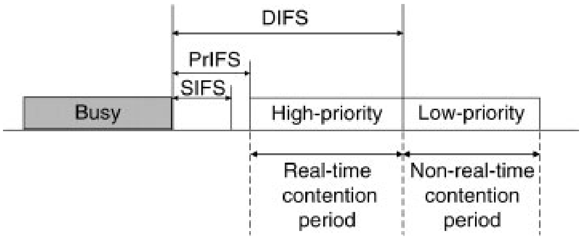

Fig. 5. The contention of real-time and non-real-time traffic in DBASE.

In summary, resource reservation is indispensable in WMNs with integrated traffic to provide multimedia support with fine-grain QoS. For real-time traffic, the main goal of channel reservation is to guarantee QoS requirements such as delay constraints. For non-real-time traffic, reservation-based schemes are also crucial in boosting the channel utilization and network throughput. In addition, it is desired to assign real-time traffic a higher priority to reserve the channel over non-real-time traffic. Combined with prioritization, channel reservation is desired for multi-purpose WMNs. However, if the QoS demand of all users outweighs available resources, QoS may be degraded. Therefore, effective call admission control is required. Also, it is unfair to starve some low-priority traffic under heavy loads of high-priority traffic. The issue of fairness should be addressed carefully in multi-purpose WMNs with integrated services.

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6. Fairness Enhancement

It is important in WMNs to maintain fairness among all nodes in the network. Although priority and resource reservation discussed in Sections 4 and 5 provide some node-wise QoS support, the issue of fairness or system-wise QoS provisioning is still yet to be addressed. In the heterogeneous WMNs, each node should be able to access the channel; otherwise, some low-priority nodes are starved and cannot transmit their packets when the traffic load from high-priority nodes is heavy. An MAC is supposed to maintain a balance of satisfying QoS demands of the users and achieving fairness of the entire system, particularly in multi-purpose WMNs with an integration of various wireless technologies and different kinds of traffic flows. As the system resources such as radio bandwidth are limited, in addition to prioritization and resource reservation, efficient resource allocation is important to meet different demands of users and preserve fairness.

6.1. Fairness in Single-Hop Networks

It is well-known that the mandatory DCF in IEEE 802.11 (CSMA/CA) can achieve good long-term fairness. However, its short-term fairness performance is poor because the binary exponential backoff favors a node with recent successful transmission [45]. If a node successfully transmits its packet, its contention window size will be reset to the initial value, giving the node more chances to win in the following contentions; if a node's transmission is collided, its contention window is doubled and, therefore, its chances to win next contentions are smaller. Thus, the wireless medium is not shared fairly by all the competing nodes in short term. To alleviate the short-term unfairness problem, a possible solution is to adjust the parameters in the backoff procedure, such as the CW, the backoff timer, or the IFS of the nodes based on the difference between expected and actual received services. One example is the distributed weighted fair queuing (DWFQ) [46]. Each node first computes the difference between the actual throughput and the expected one. It then adjusts its CW, and hence traffic priority will be adjusted accordingly. One disadvantage is that, in a highly loaded network without central coordination, congestion may make every node decrease its CW, which in turn causes the network even more congested. This issue should be addressed carefully in WMNs where there are many networking constituents working together. Another example is the distributed deficit round-robin (DDRR) [47]. A service quantum rate is introduced for each traffic class, which is proportional to the throughput requirement of the class. Nodes maintain a deficit counter of accumulated quanta for each traffic class, which is reduced by the size of transmitted frames. The deficit counter is an indication of the difference between experienced throughput and required throughput. The counter is then mapped to an appropriate IFS. A large deficit counter indicates a highly unsatisfied service and results in a small IFS, so that the corresponding traffic class is more likely to be transmitted. In addition to the amendment of the CW and the IFS, fairness can be achieved if the backoff interval of a node is adjusted according to the difference between the expected and received services [48].

The above mechanisms require significant modifications to the contention behaviors of popular MAC protocols. On the other hand, the BB contention scheme [13] discussed in the Subsection 4.3 can achieve short-term fairness with minor modifications to the EDCA. In the BB contention, as the BB length is proportional to the backoff timer value, the node with the largest timer value will have the longest BB and win the channel. When the packet from a node is collided, its CW is doubled, thus making it more likely to select the largest backoff timer and BB length, and more likely to win the next contention. A successful transmission resets the CW to the initial value, making the node less likely to win the next contention. Hence, the channel access time is distributed more fairly to all the contending nodes in short term.

The above schemes are mainly for a single-hop network to achieve per-node fairness. In the multi-hop wireless mesh backbone and wireless client networks supporting heterogeneous traffic, per-flow fairness instead of per-node fairness should be used.

6.2. Per-Flow Fairness in Multi-Hop Networks

To achieve fairness in a multi-hop network is quite challenging because of the following reasons: (1) for traditional (single-hop) cellular networks, the generalized processor sharing (GPS) [49,50] or its variants [51,52] can be applied to achieve fairness, where all the nodes share the total resources (e.g., time slots and/or code channels) in a specific link. However, in multi-hop WMNs, each node contends with its neighbors which are location-dependent, and any two flows in the network may have a direct or indirect contention relationship. Thus, the definition of fairness over multi-hop WMNs should be a global term rather than limited to a specific link; (2) fairness and spatial channel reuse may

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conflict. With sufficient space separation, two flows are allowed by spatial reuse to transmit simultaneously, which may not comply with the transmission order determined by strict fairness; (3) some global or two-hop neighbors' information may be needed to achieve fairness in multi-hop WMNs. The information exchange overhead and the possibility of inconsistent information may degrade the fairness performance [53].

An effective way to achieve flow-based fairness in a distributed manner is to use self-coordinating localized fair queuing [53]. The fairness is achieved by all the flows self-coordinating transmission decisions. A service tag containing a virtual finishing time is kept by each flow, and piggybacked in the handshaking messages of the transmission. Each flow compares its own tag with all current service tag values of its contending flows. A flow transmits if its service tag is smaller than those of its contending flows. Otherwise, the flow defers with a timer equal to the number of contending flows with smaller tags (than its own). A node is allowed to transmit if it does not detect transmission until the timer timeout. Provided with consistent information, each flow can be guaranteed with a minimal service share. The cost is the overhead to obtain and keep the service tag information of all contending flows.

6.3. Utility Optimization

To achieve fairness in multi-hop WMNs, the fairness model (such as weighted fairness, proportional fairness, and max-min fairness) can be represented by a utility function [54]. Based on a *resource contention graph*, the fairness model can be further translated into a contention resolution algorithm, where each flow adjusts a persistence probability according to its collision status. Fairness can be achieved without explicit global coordination [55].

Utility optimization framework is a powerful tool to measure system performance subject to certain constraints. With an appropriate problem formulation in the objective function(s), the corresponding optimal solutions can give rise to some sort of fairness, for example, proportional fairness [56]. However, it is difficult to formulate the problem with some varying system parameters (such as link capacity) of the wireless environment. Moreover, if the optimization problem is not trivial, common ways such as convex optimization approaches [57] cannot be directly used. Even though iterative approaches and/or intelligent searching algorithms may solve parts of the problem, the computational cost can be high, which is not suitable for the delay-sensitive applications and for some mesh clients with low processing power.

With the systematic mathematical framework, utility optimization gives a better way to address fairness than some heuristic approaches. By relaxing certain optimization constraints, some approximate results can be obtained, thereby providing performance bounds for the MAC design of WMNs.

6.4. Traffic Shaping

Generally, bursty traffic coming from one node can degrade the system performance and cause unfairness to other nodes in the network. Traffic shaping is another way to maintain fairness in the whole system by smoothing the bursty traffic and controlling the amount of traffic injected into a network. It may also contribute to efficient call admission control [49]. Two common methods are traffic smoothing and burst shaping [58] as shown in Figure 6. The traffic smoothing method

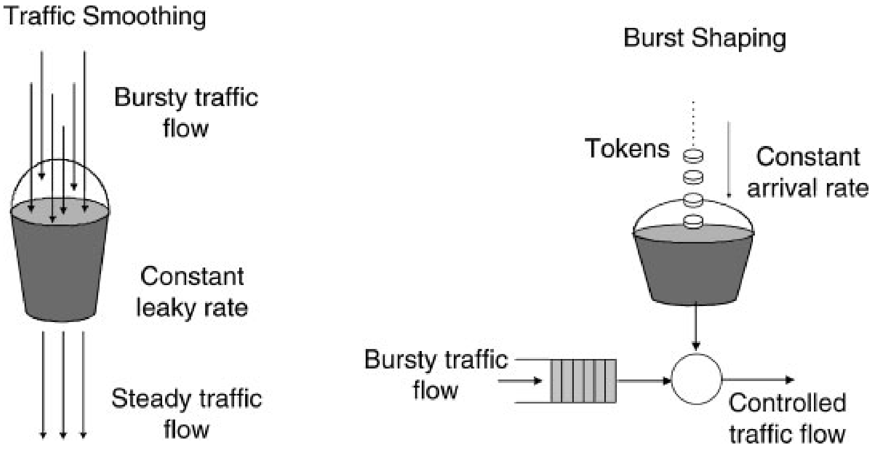

Fig. 6. Traffic smoothing and burst shaping.

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eliminates burstiness and generates a steady traffic stream to the network. On the other hand, using a token bucket, the burst shaping method allows bursty traffic to continue transmitting whenever there are tokens in the bucket, up to a user-configurable threshold. Tokens arrive at a constant rate. A flow is allowed to transmit only when there are tokens in the bucket. Therefore, bursty data traffic can be transmitted at its peak rate if there are adequate tokens in the bucket. However, urgent flows cannot be sent out in the absence of tokens, which is not desired in some applications. With various types of traffic in WMNs, traffic shaping can be helpful to keep the system traffic smooth and steady so as to maintain fairness among all nodes and achieve efficiency of the system operation [59,60].

One disadvantage of the traffic shaping is the constrained transmission rate. When the total traffic volume in the network is very low, radio resources are not fully utilized.

In summary, for the multi-purpose WMNs, different traffic flows have different QoS requirements. Distributed MAC protocols should be designed to satisfy various QoS demands without starving some lower-priority traffic, in order to maintain a certain degree of fairness. When the vulnerability of radio links and node mobility are considered, it is more challenging to achieve short-term fairness. Generally short-term fairness can be realized by using some compensation methods and/or dynamic adaptation schemes. Fair queuing, utility optimization, and traffic shaping should be carefully designed to achieve the required fairness.

7. Multi-Channel Communications

Instead of using a single data channel for transmissions (such as the case in CSMA/CA), using multiple data channels allows simultaneous transmissions in a neighborhood. Multi-channel communications can be supported by CDMA or UWB technologies. There are two main aspects, namely code (or channel) assignment and power/interference control. Code/channel assignment is necessary to allow multiple transmissions and avoid collisions to increase system throughput. As orthogonal codes or channels may not be available all the time, power/interference control is necessary to guarantee QoS for the ongoing traffic flows.

7.1. Code/Channel Assignment

To support simultaneous transmissions, techniques of direct sequence (DS) and time hopping (TH) can be employed. Multiple access can be achieved if each link uses an independent pseudo-random DS or time hopping sequence (THS). However, in WMNs, because there is no central controller, a code (or sequence) assignment protocol is necessary to determine the DSs or THSs used for traffic transmission and for monitoring any new traffic arrival over the medium. Currently, there are three basic types of code assignment protocols, namely common code, receiver-based code, and transmitter-based code [61]. When a common code is used, multiple simultaneous transmissions may collide. When the receiving code (of the receiver) is used, a collision is still possible if multiple senders send packets to a common receiver. When the sending code (of the transmitter) is used, multiple simultaneous transmissions will not collide because of the different codes used. However, the receiver needs to know its desired sender in advance in order to monitor the code channel.

In order to avoid collision and make the handshaking procedure manageable, hybrid schemes should be more effective. For example, a combination of common code and transmitter-based code results in common-transmitter-based (C-T) protocols, while a combination of receiver-based code and transmitter-based code leads to receiver-transmitter-based (R-T) protocols [61]. MACA [19] can be incorporated into C-T and R-T protocols, referred to as MACA/C-T and MACA/R-T protocols, respectively [62], as shown in Figure 7. In MACA/C-T, each node is assigned a sending code. A common code is used for the RTS-CTS dialogue, and the source's sending code is used for DATA transmission. A collision happens when multiple RTS-CTS dialogues exist in the same region. In MACA/R-T, each node has a sending code and a receiving code. The RTS is transmitted by the destination's receiving code. Then CTS is sent by the destination using the destination's sending code. After that, the source's sending code is used in DATA transmission. It can be seen that, collision only happens when multiple sources send RTS frames to a common destination using the destination's receiving code. Therefore, MACA/R-T achieves a higher system throughput than MACA/C-T.

Another multi-channel MAC protocol is called bidirectional multi-channel MAC (Bi-MCMAC) [63]. Unlike MACA/C-T or MACA/R-T in which the codes are pre-assigned, a transmitter in Bi-MCMAC sends an RTS frame containing a list of available channels in its vicinity to the intended receiver. If the RTS frame is successfully received, the receiver will check the list of its own available channels and compare it with the list of the sender's. If a common channel is found, the receiver will then select that channel and send a CTS frame with the channel information. To increase the

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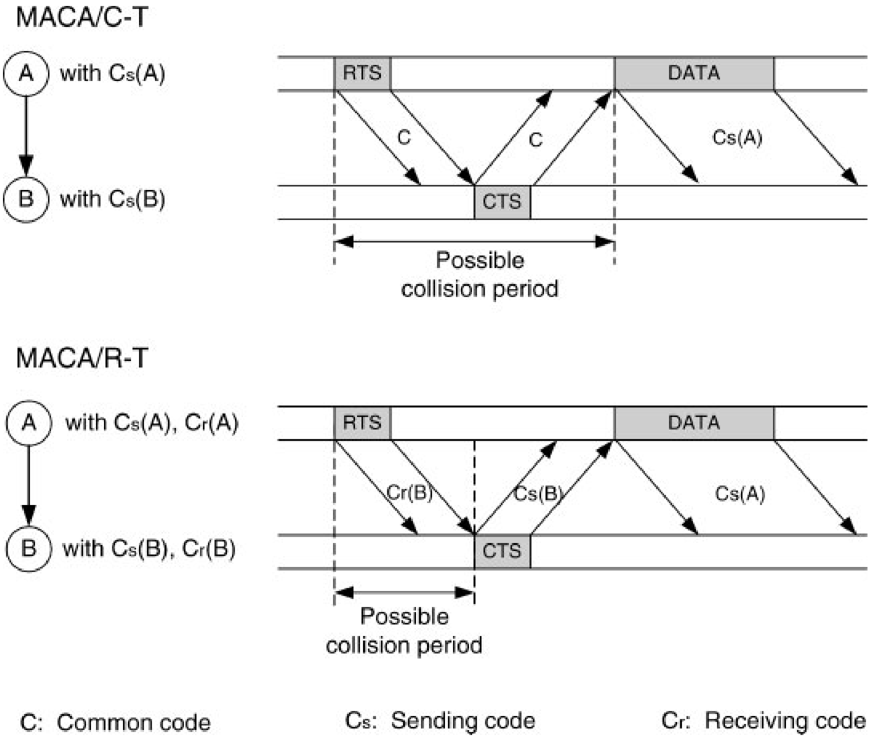

Fig. 7. The MACA/C-T and MACA/R-T protocols.

chances of successful transmission, a heuristic strategy is to let the receiver always choose the free channel used in the last successful transmission. Otherwise, the receiver simply picks the lowest-numbered channel [63]. With more freedom in DATA transmission, system performance can be improved.

With an effective code/channel assignment, simultaneous transmissions do not collide. However, code information should be known globally, which may not always be the case in distributed networks. The generated interference should also be controlled so as to guarantee the transmission accuracy.

7.2. Power/Interference Control

In spread spectrum systems, multiple-access interference (MAI) is inevitable and it gives rise to the well-known near-far problem [64]. Thus, even though different nodes use different codes for transmissions, it may not ensure successful receptions at the receivers as the interference may overwhelm the desired signal. This near-far problem can be alleviated by power and interference control.

Power can be managed in a global or incremental mode [65]. In the global mode, the power levels are re-negotiated upon a new session arrival or departure. In the incremental mode, the new session arrival or departure should not affect the existing power level assignment. While the global mode may be appropriate for centralized networks such as cellular networks, it is desired to apply the incremental mode in WMNs because of the distributed control.

The objective of power/interference control is to guarantee that the observed signal to interference plus noise ratio (SINR) at a target receiver is at least a required threshold (say γ_i for link i), that is,

$$\mathrm{SINR}_i = \frac{P_i h_{ii}}{\sum_{j\neq i} P_j h_{ji} + \eta_i} > \gamma_i, \quad \forall i \tag{1}$$

where P_i is the transmit power of link i's transmitter, h_{ij} is the path gain from link i's transmitter to link j's receiver, η_i is the background noise. Hence, for each ongoing transmission, a maximum sustainable interference (MSI) or interference margin [66,67] is defined as the additional tolerable interference while not violating the SINR requirement. That is, for link i

$$\frac{P_i h_{ii}}{\sum_{j\neq i} P_j h_{ji} + \eta_i + \mathrm{MSI}_i} = \gamma_i \tag{2}$$

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which leads to

$$\mathrm{MSI}_i = \frac{P_i h_{ii}}{\gamma_i} - \sum_{j \neq i} P_j h_{ji} - \eta_i \tag{3}$$

Each new transmission should not lead to a negative MSI of any existing transmission.

In general, the following method can be used for power/interference control in WMNs.

- Common power level: A simple solution is to select an optimal common transmit power level for all the nodes in a network. For WMNs with uniformly distributed nodes, an optimal common power level can be set to the minimum value so as to keep the network connected [68], leading to less interference.
- Clustered power level: Another way to reduce and control the interference level is by clustering [69–71]. Unlike a flat network topology, clustering allows better channel reuse. In particular, with multi-channel implementation such as in CDMA systems, lower transmission power is sufficient for intra-cluster data transmission, causing less inter-cluster interference. Distributed power control is needed to effectively control the intra- and inter-cluster interference [71]. To avoid slow closed-loop power control, successive interference cancellation (SIC) can be employed [69].
- MSI-based power/interference control: A new transmission is allowed with an assigned power level if the MSI values of existing transmissions are honored upon the new transmission joining the network. It is important to properly distribute the MSI information among the network. Some possible solutions are as follows: (1) For each existing transmission, the receiver transmits a busy-tone signal on a busy-tone channel, and the power level of the busy-tone signal is inversely proportional to the MSI. A potential new transmitter monitors the busy-tone channel, and determines the maximum power that it is allowed to transmit while not violating the MSI requirements of existing transmissions [72]. However, the approach may lose its effectiveness when two or more busy-tone signals overlap in the time duration. Also, it is possible that two or more potential new transmitters independently decide to transmit when each of them considers that the MSIs of existing links are not violated by its transmission. In this case, it is likely that the aggregate interference generated by the new transmissions may exceed the MSIs of some existing links, thus corrupting the receptions. (2) The total available bandwidth is divided into a data channel and a control channel. The MSI information is included in the CTS transmitted in the control channel. The channel gain is estimated through the received RTS/CTS frames [67].

In fact, these CDMA-based power/interference-controlled MAC schemes employ the notion of cross-layer design (discussed in Section 8) by considering both physical layer power control and MAC layer multi-channel medium access.

In summary, multi-channel transmission using CDMA or UWB has potential to increase the system capacity by allowing simultaneous transmissions. With scrutiny of code assignment and power/interference control, the system throughput can be increased and QoS support can be provided, which is desirable in WMNs.

8. Cross-Layer Design

The conventional protocol stack requires different protocol layers to be transparent to each other, making the implementation and operation simple and scalable in wireline networks. With time-varying and vulnerable wireless links, unfortunately, using the layered protocol design does not contribute to an optimal solution for wireless networks [1]. To meet this new challenge, the MAC protocol design and aspects of the other layers should be jointly considered, giving rise to the cross-layer design methodology.

8.1. Joint Physical and MAC Layers

To take account of the interference in the physical layer, collision avoidance can be achieved by power controlled multiple access (PCMA) [72], which employs handshake signaling, busy tone, and power control. The sender first transmits a Request-Power-to-Send (RPTS) frame to the receiver. The receiver then determines the minimum acceptable power by taking into account the interference level and the separation distance. Subsequently, it sends back an Acceptable-Power-to-Send (APTS) frame. While receiving the DATA, the receiver further calculates the tolerable interference level and sends a busy tone in the busy-tone channel, where the signal strength of the busy tone indicates the tolerance to additional interference. Note that this busy tone is periodically broadcast to avoid new incoming nodes from transmitting with an unacceptable power level. One key advantage is that this scheme solves the hidden terminal problem without aggravating the exposed

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terminal problem. Moreover, with power control, power consumption is reduced and, at the same time, system utilization is increased. In WMNs, if the transmission period is within the channel coherence time [73], this concept can be applied to the wireless mesh routers, which are fixed nodes and the wireless channel gains do not change with time drastically.

Employing directional antennas can largely reduce the interference in the physical layer and improve the system throughput [74]. Unlike an omni-directional antenna, a directional antenna placed at the transmitter can restrict the transmission area by beamforming, which significantly alleviates the exposed terminal problem. Thus, simultaneous transmissions are allowed, thereby increasing system capacity and throughput. A directional antenna placed at the receiver can help to solve the hidden terminal problem by blocking any signal from other unintended directions. With a line-of-sight propagation, smart antennas can be steered to the direction of interest by estimating the direction of arrival (DOA) of the signal [75]. Furthermore, with the help of short network allocation vector (NAV) [76], more simultaneous transmissions are possible and the system capacity can be increased. Similarly, by revising the operations of NAV, directional NAV (DNAV) [77] is only updated for some busy sector. A node only needs to refrain from transmitting in those busy sectors, thereby allowing transmissions in other directions and hence increasing capacity. By a practical field experiment, it has been shown that employing directional antennas improves system performance [78], achieving both space division multiple access (SDMA) and spatial multiplexing gain [79]. However, it is still an open issue how the MAC protocols exchange information with the physical layer efficiently so as to orientate the antenna in an accurate and timely manner. With node mobility, the issues of locating and tracking mobile nodes are very challenging. However, directional antennas may be managed easily in the wireless mesh backbone where mesh routers are usually stationary.

To mitigate wireless channel fading, cooperative diversity has been demonstrated to offer significant improvement in link reliability [80–82]. The basic idea is that, if the channel between a sender and a receiver is poor, an available node nearby can help the sender relay its data through some cooperation protocols such as distributed space-time block coding (STBC) [80]. An efficient cooperative MAC protocol can provide additional robustness against fading and packet collisions, due to cooperative diversity gain [83]. However, it is an open issue to design an optimal cooperative MAC scheme based on channel conditions. How to make sure that all the nodes in the network are willing to cooperate is another challenging question. Though this cross-layer design is still at the infancy stage, provided with the knowledge of channel conditions, adaptive cooperative MAC protocols are expected to be useful in throughput enhancement and QoS support in WMNs.

8.2. Joint Physical, MAC and Transport Layers

In wireline networks, packet loss is mainly due to the congestion in the network, which triggers a congestion control mechanism such as in transmission control protocol (TCP) at the transport layer. However, in wireless networks, in addition to traffic congestion, packet loss can also be ascribed to vulnerable radio links or collisions. The conventional TCP cannot differentiate the packet losses due to congestion from those due to weak wireless links or collisions, thereby causing performance degradation. With cross-layer design, the information of packet losses in the physical and MAC layers can be reported to the transport layer. By obtaining more accurate link and network conditions, corresponding congestion control and/or power control can then be triggered [84], thereby improving the system performance.

8.3. Joint Physical, MAC and Application Layers

By monitoring channel conditions, a virtual MAC (VMAC) [85] estimates the achievable service quality (such as delay, jitter, and packet loss) at the MAC and the application layers. These estimates are important for admission control which is essential to support QoS such as a bounded average packet delay of the ongoing admitted flows in the network. The information of the physical channel conditions facilitates admission control. With VMAC, the estimates of service quality parameters can be used by the application layer to adjust the traffic parameters such as data rate. However, the tradeoff is the implementation complexity of interactions between MAC and application layers. The operation of MAC protocols affects the performance in the application layer while the performance of MAC protocols is dependent on the physical channel conditions. Thus, information exchanges among the physical layer, MAC layer, and application layer are mandatory in order to increase the degree of satisfaction of end-users in WMNs.

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In summary, cross-layer-based MAC protocol design is expected to be very promising as it optimizes the whole system by exploiting primitive system parameters across different layers. Cross-layer information should be distributed and shared among all the involved protocol layers. Such information can be included in packet headers, managed by a third-party network service, or stored in system profiles which are available to the related layers [86].

9. Open Research Issues

Location Awareness. Without mobility, a mesh router can know the exact locations of other mesh routers. MAC design can benefit greatly from the network topology information. (1) With location information, flooding can be avoided in routing. A forwarding direction can be chosen according to location information of the destination [87–89]. Moreover, based on location information, the nearby wireless routers can form a group, and a group leader can be selected for resource allocation and routing in the group. Efficient route discovery and resilient route maintenance can be achieved [88]. With an effective routing mechanism, complexity can be reduced in the joint routing/MAC design. (2) According to location information of a node's neighbors, the transmission power, rate, and time can be selected appropriately to achieve required transmission accuracy and not to corrupt transmissions in the neighborhood. (3) The location information can also help to solve the hidden terminal and exposed terminal problems more easily. (4) With location information, each wireless router can estimate the contention level in its neighborhood and the amount of available resources, which are needed for QoS routing. Also, MAC parameters can be selected according to the contention level at a node. For example, for CSMA-based MAC, a node in a sparse area can use parameters (e.g., power levels and backoff parameters) in its transmission different from those of a node in a dense neighborhood [16].

Multiuser Diversity and Fairness. To exploit the time-varying nature of wireless channels, multiuser diversity mechanisms can achieve a certain capacity improvement. Multiuser diversity mechanisms are a kind of cross-layer design between the link and physical layers. The principle of multiuser diversity is originally proposed for a cellular system with multiple mobile nodes having independent time-varying fading channels. It is very likely that there exists a node with instantaneous received signal close to its peak value. The overall resource utilization is maximized by providing service at any time only to the node with the best instantaneous channel quality [90], with the aid of a central controller. For distributed WMNs, how to achieve multiuser diversity is a challenging issue. It should be jointly considered with routing. Also, highly adaptive MAC and reliable mechanisms for information exchanges are needed to keep track of time-varying wireless channels. On the other hand, multiuser diversity mechanisms may give rise to unfairness. If a node with real-time traffic is in a poor channel state for a relatively long period, a multiuser diversity mechanism may starve this transmission, leading to a large delay and even packet dropping due to delay bound violation. The multiuser diversity mechanism for real-time services needs to be carefully designed [91].

QoS in Multi-Channel Transmissions. QoS provisioning on multi-channel MAC is challenging. For example, the fairness enhancement mechanisms discussed in Section 6 are mainly for a single-channel network. However, if multi-channel MAC is applied to WMNs, a node cannot monitor all the code channels used for other nodes' transmissions. Thus, an information exchange mechanism by 'overhearing' may not work well, and an extra message exchange procedure is needed. Furthermore, due to the interference-limited nature, fairness mechanisms in multi-channel WMNs should be jointly designed with power and rate allocation. Also, a multi-channel scenario using multiple frequency bands for transmission brings about more challenges [92]. For example, as different frequency bands experience different channel fading, dynamic resource reservation and allocation are needed. Power allocation on different frequency bands gives rise to different hidden terminal and exposed terminal scenarios. Routing is also more complex due to the different dynamics in bandwidth availability, contention level, and link connections among the frequency bands.

Joint Power Control/Routing/Scheduling in Multi-hop Transmissions. To achieve end-to-end QoS support for multi-hop transmissions, both routing and MAC should be jointly designed. To achieve QoS over a hop, the MAC protocol needs to determine the transmit power, rate, or time. Also, a route needs to be chosen carefully to ensure QoS satisfaction among all the hops according to bandwidth availability and traffic load distribution. A well-designed routing can distribute bandwidth requirements appropriately among the nodes, thus facilitating the QoS provisioning in MAC, while the MAC protocol can determine the service quality (e.g., queuing delay) seen from the routing protocol, and affect the route selection. Hence, performance improvement is expected from joint design of

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routing and MAC, at the cost of increased complexity [93]. As mentioned, some power control solutions in the literature [72,94] can manage the transmit power level just enough to ensure successful reception at the desired receiver to achieve minimal interference. However, this *local optimization* may not lead to the global optimization in the whole network. Hence, power control also needs to be jointly considered with the routing in the network layer [95]. Furthermore, when the traffic load in the network layer is low, it is desired to use a relative high power level in order to reduce the number of hops. On the other hand, with a high traffic load in the network, a lower power level can achieve a lower contention level at the MAC layer [95]. Although some preliminary results have been presented in the literature [96], more in-depth investigation is needed.

Traffic Prediction and Traffic Load Awareness. In the three-tier architecture as shown in Figure 1, the aggregate traffic from/to mesh client networks is via mesh routers. Therefore, it is important to predict the traffic load from/to the mesh client networks so as to design efficient MAC for the wireless mesh backbone. Also, in the wireless mesh backbone, the traffic load varies from one mesh router to another. Generally, the routers near the wireline gateways may have high-traffic load. Hence, the MAC in wireless mesh backbone is desired to be traffic load aware. For example, the transmit power of mesh routers close to wireline gateways may be small so as to reduce the contention level. Routing should also be taken into account as it affects the distribution of traffic load in the whole WMN.

Heterogeneous Design for Mesh Routers and Clients. Mesh routers are usually stationary and do not have power-consumption constraints. Thus, an MAC protocol for mesh routers is not necessarily the same as the one for mesh clients which are mobile and need some power-saving MAC schemes. Also, as some mesh routers are connected to different existing wireless access networks such as cellular networks and WLANs, they may need to support multimedia traffic with QoS provisioning and fair resource sharing among different classes of traffic flows. For mesh clients, MAC protocols based on best-effort service, priority, or reservation can be employed, depending on the objectives of network design. Due to power-consumption constraints and user mobility, the protocols should be power efficient and channel-aware in order to enhance system performance.

Scalability in Large-Scale WMNs. For a WMN covering a large area, for example, a city, scalability is one of the major concerns for QoS provisioning. When traditional resource reservation approaches are applied to the wireless mesh backbone, although fine-grain QoS can be achieved, the per-flow reservation and signaling may bring a severe scalability problem. For wireline core networks, differentiated services (DiffServ) has emerged as a scalable approach. Accordingly, a *wireless DiffServ* architecture is proposed in Reference [5] to address the scalability issue over the wireless mesh backbone. The wireless DiffServ is quite different from the wireline DiffServ due to the unique architecture of the wireless mesh backbone: (1) in wireless DiffServ, a wireless router may serve as both the edge router and the core router; (2) in wireless DiffServ, a centralized controller (such as the bandwidth broker used in wireline DiffServ) is not available. The resource allocation should be executed in a distributed manner, thus posing challenges; (3) in wireline DiffServ, the links among the routers have constant bandwidth, thus service provisioning is usually performed at the network layer. While in wireless DiffServ, due to the wireless broadcasting environment and shared medium, the physical and MAC layer should also be taken into account when DiffServ QoS is provisioned. The design of MAC protocols tailoring to wireless DiffServ is a challenging issue.

Game Theoretic Approach. Game theory [30,97] is a mathematical formulation for the analysis of game dynamics. In distributed networks, a game theoretic framework is a useful tool for distributed resource allocation, where each node or player interacts with others in a distributed manner. With properly defined utility functions, fair resource allocation and enhanced system performance can be achieved by game theoretic approaches [98,99]. However, heterogeneous networking characteristics in WMNs make the game design more complex. A game player may have different game policies in the wireless mesh backbone and wireless mesh client networks. Novel game theoretic policies and algorithms specially targeted for WMNs are needed to achieve the Nash equilibrium and Pareto optimality [97].

10. Conclusion

WMNs consisting of mesh routers and mesh clients are dynamically self-configured and self-organized distributed networks with an integration of various existing wireless technologies. This novel networking paradigm offers a viable solution to wireless multimedia QoS support with the help of distributed MAC protocols. The unique characteristics of WMNs determine that existing MAC protocols may not work well. We have investigated the feasibility and drawbacks of the existing distributed MAC protocols when they are implemented in WMNs, in the avenues of best-effort service support, priority guarantee, resource reservation, fairness enhancement, multi-channel communications support, and cross-layer design. All these discussions indicate that the design of novel distributed MAC protocols for multi-purpose WMNs is necessary to utilize the network resources efficiently, and to achieve good system-wise and user-wise performance. Open research issues include location-aware and traffic load-aware heterogeneous MAC, opportunistic transmissions, QoS in multi-channel communications, end-to-end QoS support, cross-layer design, scalability, and game theoretic approaches.

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