Wait-Time-based Multi-channel MAC Protocol for Wireless Mesh Networks

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***Abstract*—The dedicated control channel protocols can solve many problems in multi-channel environments by using a common control channel to exchange control frames. However, the overhead produced in channel consultation are costly and easily lead to Control Channel Saturation (CCS) problem, which reduces both the network throughput and channel utilization. In this paper, we propose a new multi-channel MAC protocol, named Wait-Time-based Dedicated Control Channel (WTDCC) protocol to solve the CCS problem. Our scheme can drastically reduce the overhead for consultation on the control channel and make full use of all the data channels. Theoretical analysis and simulation results show that the WTDCC can improve the throughput of each data channel, and the common control channel can support negotiation for more data channels. Thus more orthogonal channels can be used and the system performance can be improved.**

***Index Terms*—wireless mesh networks, multi-radio, multi-channel, medium access control, control channel saturation**

I. Introduction

Wireless mesh networks (WMNs) [1-3] have gained acceptance from both industry and academia as a cost-effective approach to support high speed last mile connectivity and ubiquitous broadband access because of their favorable characteristics, such as robustness, highly flexible, low up-front costs, deployment cost-effective self-organization, self-configuration, self-healing and easy maintenance. Illustrated in figure 1, WMNs consist of mesh router (MRs) and mesh clients (MCs) where MRs have minimal mobility and forward packets for other nodes that may not be within direct wireless transmission range of their destinations. Some MRs act as mesh gateways (MGs) between WMNs and external networks such as the Internet.

One major challenge in WMNs is the capacity reduction due to wireless interference. In the traditional wireless network, only one interface is equipped at each node and all nodes share a single channel. Research revealed that the capacity per node in such scenario drops significantly with the increase of the network size. It was demonstrated in [4, 5] that in a multi-hop network with all links running the same IEEE 802.11 protocol, the end-to-end performance suffers low throughput and unfairness problems.

In WMNs, some nodes equipped with more than one radio interface worked on different channels, formed a multi-channel WMN. There is a wireless link between two neighboring nodes whose interface worked to the same channel. This architecture allows enhanced aggregate network throughput by breaking collision domain into multiple collision domains which operating on multiple non-overlapping channels and exploiting co-channel reuse, i.e., simultaneous transmissions will occur if transmitting nodes use orthogonal channels. Utilizing multiple channels within the same network substantially increases the effective bandwidth available to wireless nodes [6, 7]. Whereas, it also brings some new problems in MAC layer, such as reducing the network connectivity (network partition) and broadcast problem, multi-channel hidden terminal problems, deafness problem [8-10].

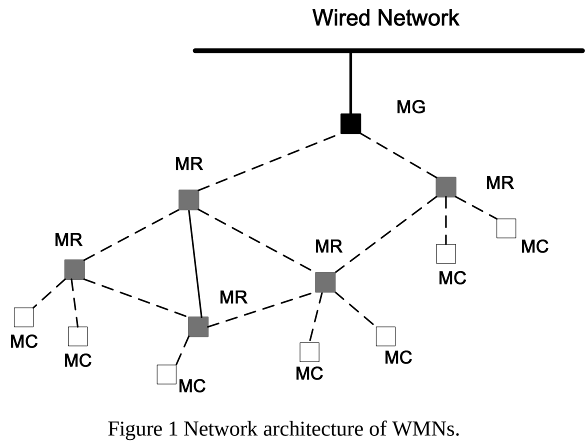

Figure 1 Network architecture of WMNs.

Many protocols [8-10] were proposed to solve the above problems. These methods were categorized into four categories, which are namely split phase, common hopping, multiple rendezvous and dedicated control channel, by Mo et al. [11]. For split phase protocols [12-15], time is divided into channel negotiation phase and data transmission phase. Those nodes which have packets to transmit negotiate and reserve channels during the channel negotiation phase on-demand on a default channel, and exchange data/ack packets in the data

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window on multiple channels concurrently. The benefit of split phase protocols is that MAC layer broadcast primitive can be performed during channel negotiation phase, since all nodes switch to the common channel during the negotiation phase.

For common hopping protocols [16], all nodes follow a common channel hopping sequence and don't exchange data hops through all channels synchronously. A pair of nodes stops hopping as soon as they make an agreement for transmission and rejoin the common hopping pattern subsequently after transmission ends.

In contrast with common hopping protocols, every mobile node in multiple rendezvous protocols [17, 18] has its own hopping sequence that partially overlaps with others nodes and allow nodes to rendezvous simultaneously on different channels. Since there are multiple rendezvous channels, special coordination is required so that two devices can rendezvous on the same channel. When the source and the destination are on the same channel, data/ack exchange procedure can be preceded. The sender actively switches to the receiver's current channel for communication.

Though the above three protocols only require one network interface, they either need time synchronization or do not completely support MAC layer broadcast because nodes do not always listen to the same channel. Unfortunately, tightly time synchronization is very costly in ad-hoc networks, especially in multi-hop scenario. Besides, absence of MAC layer broadcast is the main reason to problems in multi-channel WMNs, such as multi-channel hidden terminal problems, deafness problem and broadcast problem [8-10]. Thus, supporting efficient MAC layer broadcast in multi-channel MAC protocol is a key challenge [19].

The dedicated control channel protocols [20-22] solve the MAC layer broadcast problem without require time synchronization by using a dedicated control channel. In these protocols nodes need two (or more) radio interfaces, namely the control interface and the data interface. The control interface always stays on a specific common channel (called control channel), while the data network interface can be dynamically switched to any other data channel (called data channels). The control channel is used to negotiate channel when a node has data to transmit. After channel negotiation, nodes switch the data interface to the selected data channel, and exchange data/ack packets. Since nodes always listen to the common channel, they can broadcast packets on the common channel. Moreover, dedicated control channel protocols do not require time synchronization, since channel negotiations are performed on the common channel.

However, there are two major challenges in DCC protocols. Firstly, the DCC protocols consider each packet transmission as an independent mission. When a packet arrives, the channel negotiation will perform and a data channel is arranged to transmit. Moreover, the channel negotiation for each data packet of all nodes was held on the control channel. When too many nodes consulted on it, the control channel would be saturated and became a bottleneck of the overall performance [11]. The data channels cannot be fully utilized because of CCS (Control Channel Saturation) problem when too many short data packets are generated. In order to reduce the overhead of channel negotiation, COMMAC was proposed in [21] which suggest that the sender firstly proposed a free channel in the RTS. If this channel is free to the receiver, the data transmission can be started immediately after received the CTS. Otherwise, it follows the same way with DCA. COMMAC can reduce some of the RES packet, but the overall overhead of control channel is roughly equal to the DCA. Secondly, the existing channel negotiation only considers the presence of idle channel for the two sides. If there not exist the available channel, the consultation would continue until a common free channel is found for both sides. If there more nodes and more heavily loaded in the networks, a large of overhead were brought and more resources are wasted.

The above DCC protocols [20, 21] are mainly designed for mobile Ad Hoc networks in which all nodes are mobile, the traffic is burst and the channel quality fluctuates rapidly; therefore channel consultation was need for each data frames. However, nodes in WMNs are stationary; the traffic is heavy, but relatively stable. Therefore, it is unnecessary to negotiate channel for each packet. This motivates us to propose a new dedicated control channel protocol. It consists of two parts: (1) Improved channel selection mechanism (ICS). When there not exist the idle channel for both sides, the channel which has minimum waiting time was selected. (2) Data channel scheduling mechanism (DCS). Several data frames were transmitted on each data channel after a success consultation on the control channel. Theoretical analysis and simulation results show that our protocol can substantially improve the throughput in both single-hop and multi-hop networks.

The rest of this article is organized as follows: In Section 2, we theoretically analyzed the reasons and main factors which lead to CCS. Section 3 describes the basic operation of the WTDCC protocol. The detailed design of each component is present in Section 4. The simulation results are discussed in Section 4. Section 5 makes a conclusion.

II. The CCS Problem

In the DCC protocol, channel negotiations for all links are held on the control channel. When the control channel was saturated, the data channels lack of timely channel consultation and became idle. Thus the performance of the network has been limited due to the saturation of the control channel. This is CCS problem.

DCA was used as an example to explain the CCS. Shown in in figure 2, R, C, E means the RTS, CTS, RES frame, respectively. Channel D0 was used as a control channel, the remaining four for the data channel (assuming a bandwidth of B). When links worked on different channels, the network throughput can reach 4B theoretically. In the figure, the control channel was jammed with the control frame for consultation, and it

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can only provide consultation support for three data channels. So the fourth data channel never can be used. That is to say, the network throughput only can reach 3B. When the network node density is large, available channel number rise or data transmission speeds are higher, CCS problem will become more serious.

For each link, the idle time for control channel is the

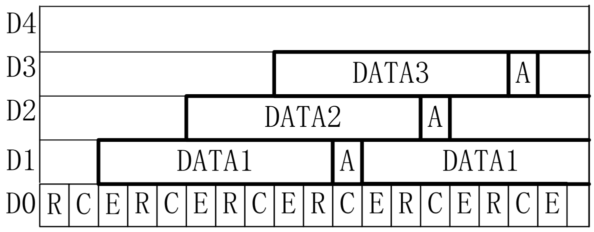

Figure 2 Control Channel Saturation [12].

times which transmit packets on data channels. It is the time which control channel can be used for other links. To provide consultation support for the entire data channel, there must be

$$B_A \geq B_D \quad (1)$$

Where B_A is the average bandwidth provided by the control channel, B_D is the required average demand bandwidth of the control channel which support consultation for m_D data channels, and given as follows:

$$B_A = \frac{L_{RTS} + L_{CTS} + L_{RES}}{t_C} \quad (2)$$

$$B_D = \frac{m_D \times (L_{RTS} + L_{CTS} + L_{RES})}{t_D} \quad (3)$$

Where L_{RTS} , L_{CTS} , L_{RES} means RTS, CTS, RES size, the t_C means the time which completed a consultation on the control channel and t_D means the time complete a data transmission on the data channel, and given as follow:

$$t_C = T_{DIFS} + T_{D\_RTS} + 3T_{SIFS} + T_{D\_CTS} + T_{D\_RES} + \overline{CW} + 3\tau \quad (4)$$

$$t_D = T_{DIFS} + T_{D\_DATA} + T_{SIFS} + T_{D\_ACK} + \overline{CW} + 2\tau \quad (5)$$

Where T_{DIFS} , T_{SIFS} is DCF interframe space and short interframe space, T_{D_RTS} , T_{D_CTS} , T_{D_RES} , T_{D_DATA} , T_{D_ACK} means transmission time for RTS, CTS, RES, data frame and ACK frame[23], $\overline{CW}$ is average back off time, τ is the propagation delay. Therefore, we have $m_D \leq \frac{t_D}{t_C}$.

Figure 3 show the data channel number which can be fully used by the dedicate control channel. When the payload size is 500 bytes, the data rate is 1Mbps, the dedicate control channel can support negotiation for 3.68 data channels in the ideal case. When the data rate increase to 2Mbps, this number decrease to 2.44.

III. THE WTDCC PROTOCOL

A. Overview

Similar to the DCA, at least two wireless interfaces are equipped on each node of WTDCC. One is used as control interface and exchanged the RTS-CTS-RES frames on the control channel to coordinate channel. The others are used for transmitting the data and ACK packets on the reserved channel.

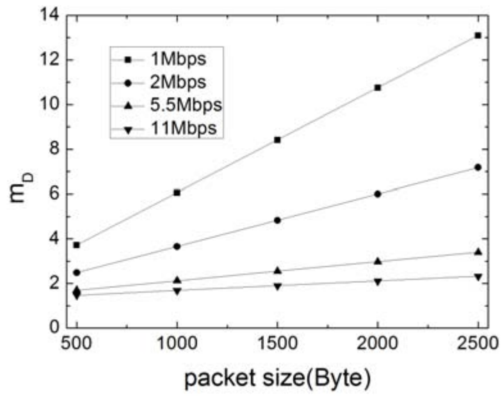

Figure 3 The maximum of m_D.

Each node maintains a WT (Waiting Time) list which records the time that the nodes must wait if it wants use each channel. Apparently, when channel i is idle, the corresponding WT_i is zero. SChB was used to record the last channel which the data interface worked on; the TrNu (transmission number) was used to record the number of packets each transmission.

To communicate with node B, A will firstly update the WT list in accordance with equation (5) and immediately send a RTS to B which carrying its WT on the control channel, whether or not there is an idle channel. After received the RTS, node B updates its WT list with equation (6) and selects a channel according to both WT lists and replies a CTS to A which carry the selected channel (for example *j*) and corresponding waiting time (such as WT_j). After received CTS, A broadcasts a RES which carrying the selected channel and the waiting time to inform its neighbors. All neighbor nodes of A/B update the NAV of channel after received the RES/CTS.

B. Improved Channel Selection(ICS)

In existed DCC protocols, the sender initiates channel consultation when there is at least one free channel. Only there is at least one common free channel for both sides, the consultation would be successful. Otherwise, more negotiation for channel was need. When the number of consultations increases, the overhead on the control channel will increase exponentially. The aim of ICS is to reduce the overhead of the control channel by reducing the number of consultations. The channel selection procedure used by receiver is described as follows.

1. If there is only one free channel (the waiting time is less than or equal to zero), then this channel was selected.

2. If there are multiple candidates exist, if channel SChB is free, then it is selected.

3. Else the channel with the lowest waiting time will be selected.

The WT of channel i on sender S was updated as follows

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$$WT_S^i = \max(0, NAV_i - (NOW + T_{DIFS} + T_{RTS} + 2T_{SIFS} + T_{CTS})) \quad (5)$$

Where NAV_i is the network allocation vector of channel i , NOW means current time.

The WT of channel j on receiver R was updated as follows

$$WT_R^j = \max(0, NAV_j - (NOW + T_{SIFS} + T_{CTS})) \quad (6)$$

The WT may be smaller than zero, which means the idle time between two consecutive data transmission. The receiver calculates the WT for all channels for both sides as follow.

$$WT_i = \max(WT_S^i, WT_R^i) \quad (7)$$

Note that the receiver can always select a channel, even if all the channels are used in the receiver's transmission range. ICS can mitigate the CCS problem, but can't completely solve it. So DCS were proposed.

C. Data Channel Scheduling (DCS)

The above DCC protocols [12-13] are mainly designed for mobile Ad Hoc networks in which all nodes are mobile, the traffic is burst and the channel quality fluctuates rapidly; therefore channel consultation was need for each data frames. However, nodes in WMNs are stationary; the traffic is heavy, but relatively stable. Therefore, it is unnecessary to negotiate channel for each packet. The DCS will send multiple data packets in each data transmission to solve the congestion in the control channels.

Assuming the control channel can transmit all the frames which negotiate for data channels if TrNu data packets sent after each channel consultation. Then we have

$$t_D^{'} = T_{DIFS} + (T_{D\_DATA} + 2T_{SIFS} + T_{D\_ACK} + 2\tau) \times TrNu + \overline{CW} \quad (8)$$

From (1), (2), (3), (4), (8), we can get

$$TrNu \geq \frac{m_E t_C - (T_{DIFS} + \overline{CW})}{T_{D\_DATA} + 2T_{SIFS} + T_{D\_ACK} + 2\tau} \quad (9)$$

Obviously, the more packets sent after each negotiation, the least overhead will be generated on the control channel. However, if too many packets were transmitted after each channel consultation, the data channels would be occupied by some links for a long time, which may incur unfairness problem to other competitors who are intended to access the data channels. Therefore, in our protocol, the minimum valued satisfies the formula (9) was selected for TrNu.

D. Theoretical analysis

The data rate of each channel in the physical layer is B, and then the effective bandwidth of each data channel in DCA protocol is

$$B_{DCA} = B \times \frac{8T_{DATA}}{t_C + t_D - (T_{DIFS} + \overline{CW})} \quad (10)$$

The effective bandwidth of each data channel in WTDCC is

$$B_{WTDCC} = B \times \frac{8T_{DATA}}{\frac{t_C}{TrNu} + t_D - (T_{DIFS} + \overline{CW})} \quad (11)$$

When $TrNu > 1$, B_{WTDCC} will increase with a decrease of the denominator of equation (11). That is to say, the throughput of each data channel will be improved.

The system throughput S is equal to the number of data channels multiplied by the effective bandwidth of each data channel [11]. So the throughput of WTDCC can be expressed as $S = m_E \times B_{WTDCC}$. Due to reducing overhead by using multi-frame continuous transmission, the effective bandwidth of each data channel was improved. Moreover, more channels are used simultaneously in the network. Hence, the throughput of the network can be dramatically improved.

IV. Simulation Results and Analysis

A. Simulation parameters

The Network Simulator 2 (NS-2) is used to evaluate the performance of the WTDCC protocols. Both single-hop and multi-hop network topology are used in our simulation. All nodes use the same transmit power and transmission range of each node is 250m; the carrier sense range is 550m. The two-ray ground reflection model is used to model radio propagation. The number of channels is set to 12. All simulations are carried out for 200 second and the routing protocol used is AODV (Ad hoc On-demand Distance Vector routing). Aggregate throughput over all the flows in the network is used as performance metrics, which is defined as the sum of the throughput of all flows.

B. Single-hop scenario

In single-hop scenario, a simple simulation is first performed with only two pair of nodes at a distance of 100 m. Figure 4 the throughput when there are two data flows in the network with various loads. When the network load is low, WTDCC and DCA perform the same. The WTDCC achieves a 204% and 119% gain compared with the DCF and DCA when throughput reaches saturation. The effective bandwidth of the data channel was improved by reducing the number of consultations.

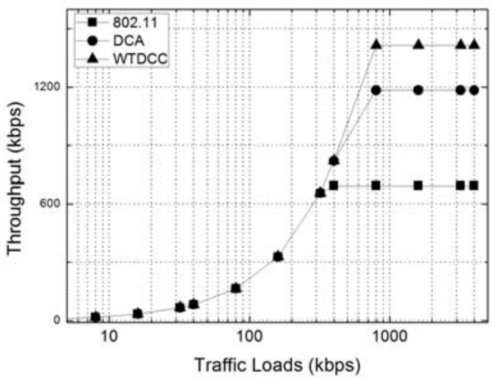

Figure 4 Network throughputs of two flows.

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Figure 5 shows the throughput when there are more data flows in the network. From the figure, we can get there only 3 data channels can be fully used in DCA. That means others 8 data channels cannot be used due to lack of consultation. In WTDCC, all of the data channel can be fully utilized and system performance is about four times as great as that of DCA. This fully verifies the validity of our protocol and the correctness of the preceding analysis.

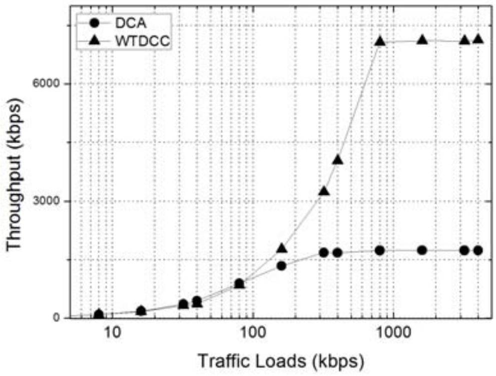

Figure 5 Network throughputs of multiple flows.

C. Multi-hops scenario

Figure 6 shows the aggregate throughput of WTDCC and DCA3R (3 radios equipped on each nodes of DCA) in a chain of 6 nodes, which are placed at a distance of 200 m from neighboring nodes. Traffic of various loads is sent from node 1 to node 6. In multi-channel multi-hop scene, the bandwidth of the path is equal to the bandwidth of a single link if adjacent link work on the orthogonal channel [24]. However, the bandwidth in DCA only reaches 65% of the maximum bandwidth (the maximum bandwidth provided in 802.11 DCF can be get from Fig.3). The main reason for this phenomenon is that each packet at least needs one data consultation on every link, resulting in a lot of overhead, and reduces the path of effective bandwidth. Overhead in WTDCC protocol was greatly reduced. Thus the throughput obtains 152% gain compared with DCA.

V. Conclusion

The DCC protocols solve the MAC layer broadcast problem by using the dedicated common channel. When too many nodes consulted on it, the control channel would be saturated and became a bottleneck. In this paper, an efficient dedicated control channel protocol is proposed, which can solve the control channel saturation problem. Theoretical analysis and simulation results show that WTDCC can not only improve the throughput of the data channel, but also make more data channels fully exploited simultaneously. So the system performance can be improved.

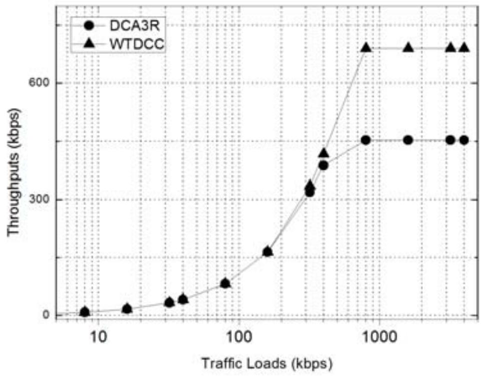

Figure 6 Network throughputs of multi-hop WMNs.

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