A Medium Access Control Protocol for Multi-Channel Multi-Interface Wireless Mesh Network

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Abstract

In recent years, Wireless Mesh Network (WMN) which uses a multi-hop configuration to extend the reach of the last-mile access to Internet has come into public notice. WMN improves network performance by the use of multiple orthogonal (non-overlapping) channels and multiple wireless interfaces. However, the Medium Access Control (MAC) protocol in IEEE 802.11 standard was designed and suited for only one channel and one interface, so we need a new MAC protocol suited for multi-channel and multi-interface in WMN. In this paper, we propose a new MAC protocol for WMN which employs a hybrid channel assignment strategy. Thus we can solve the rendezvous problem easily. In order to solve multi-channel hidden terminal problem, the proposed protocol employs a waiting time scheme to update network allocation vectors (NAVs). Moreover, we employ a dynamic staying period scheme and a dynamic waiting time scheme to improve the utilization of both interfaces and channels. In simulation results, the proposed protocol outperforms the previous MAC protocol with hybrid channel assignment.

1 Introduction

In recent years, WMN (Wireless Mesh Network) which uses a multi-hop configuration to extend the reach of the last-mile access to Internet, has come into public notice. It is based on IEEE 802.11 and deployed as mesh networks to provide wireless distribution system to let APs (Access Points) connect to the internet without wired connection. WMN is an uncentralized network and makes a set of APs to interconnect via IEEE 802.11 links by themselves. It can dramatically reduce the cost of deploying a large scale WLAN (Wireless Local Area Network) network because of the absence of wired connection. For the satisfactory of wireless broadband networks, WMN is characterized by the use of multiple orthogonal (non-overlapping) channels and multiple wireless interfaces.

The IEEE 802.11 standard has divided the available frequency into multiple orthogonal channels. For instance, IEEE 802.11b provides 3 orthogonal channels in the 2.4 GHz spectrum, and IEEE 802.11a provides 12 orthogonal channels in the 5 GHz spectrum. By assigning different channels to adjacent APs, the interference between APs in infrastructure networks can be greatly reduced. However, the current IEEE 802.11 standard allows only one channel to be used at any time. So if we can make use of all available channels interchangeably, the interference can be further reduced and the overall capacity will be improved. Nevertheless, the MAC protocol in the standard was designed and suited for only one channel and one interface, so we need a new MAC protocol suited for multiple channels and multiple interfaces in WMN.

Wireless hosts have typically been equipped with one interface. There were many researches [1, 2, 3, 4, 5] utilizing multiple channels with one interface because they consider that it is expensive to equip each host with multiple interfaces. However, with the trend of reducing hardware costs [6] and in order to utilize multiple channels efficiently, there have been many proposed MAC protocols [7, 8, 9, 10, 11, 12, 13, 14] using multiple interfaces.

There are two main problems encountered by all related works in designing multi-channel MAC protocols. The first problem is rendezvous problem and the second is multi-channel hidden terminal problem. We will introduce them below.

1.1 Rendezvous problem

Before a pair of mobile hosts wants to do communication, each of them has to know which channel the other is on. Mo et al. [15] classified all multi-channel MAC protocols into two classes, single rendezvous and multiple rendezvous. In single rendezvous protocols [2, 3, 5, 10, 11, 12], the exchange of control packets occurs on only one channel, called the control channel, at any time. These protocols will result in the control channel saturation problem because there is high contention on the control channel when the number of data channels is large. This problem makes the control channel to be a bottleneck and causes inefficient utilization of data channels. In multiple rendezvous protocols [1, 4, 7, 8, 9, 13, 14], mobile hosts can exchange control packets on many channels. The protocols of this class alleviate the rendezvous channel saturation problem but raises the challenge of ensuring the communicating pair being able to meet on the same rendezvous channel. The proposed protocol in this paper belongs to this class but it can ensure the communicating pair being able to meet each other.

1.2 Multi-channel hidden terminal problem

The IEEE 802.11 DCF mechanism can avoid the the hidden terminal problem. However, in multi-channel multi-interface environment, this problem can be further complicated. Consider the scenario in figure 1. All mobile hosts are within each other's transmission range. Host A wants to send a data packet to host B by sending an RTS packet on Channel 1 and then B responds a CTS packet. During the negotiation of A and B, host C and host D are in transmission on Channel 2 so that C can't hear the CTS packet from B and doesn't know the transmission occurs on Channel 1. After the end of communication between C and D, C might initiate a communication with B and send RTS packet on Channel 1. It will cause a collision at host B.

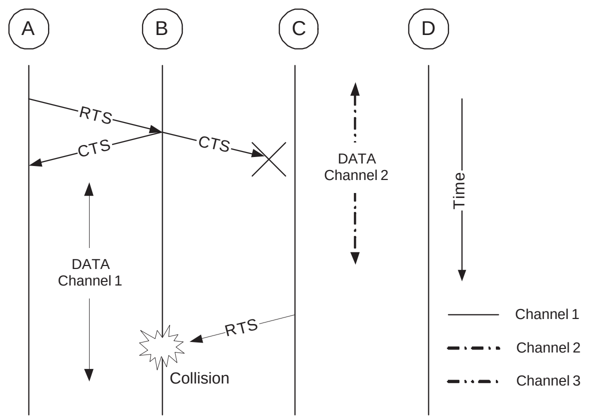

Figure 1: Multi-channel hidden terminal problem.

The above problem is called multi-channel hidden terminal problem. Wu et al. [10] and So et al. [2] have already addressed this problem. Mobile hosts may listen to different channels and each host on selected channel can't hear RTS and CTS packets sent on other channels so that it is difficult to use virtual carrier sense function to avoid the hidden terminal problem. There have been many researches which solve this problem by a separate control channel [10, 11], a time synchronization scheme [1, 2, 4] or a waiting delay [3, 5, 14]. We will introduce these in the next section.

In this paper, we propose a new MAC protocol for multi-channel multi-interface WMN. Our protocol is based on the hybrid channel assignment strategy. In this strategy, each node is equipped with a fixed interface and a switchable interface. The fixed interface must stay on a fixed channel for a long-term period and the secondary interface can be switched among multiple channels. Each host can know the fixed channels of its neighbors and communicate with them by switching its switchable interface to its neighbors' fixed channels. Thus, inherently this strategy can solve the rendezvous problem.

The rest of the paper is organized as follows. In Section II, we discuss the related works and compare them with our protocol. In Section III, we present our MAC protocol for multi-channel and multi-interface wireless network. We describe our simulation model and discuss the results of our simulation in Section IV. Finally, we conclude this paper in Section V.

2 Related works

There have been many related works about multi-channel multi-interface MAC protocol. They can be classified into the static channel assignment strategy and the dynamic channel assignment strategy. We will discuss these two strategies and introduce a new channel assignment strategy being able to avoid their drawbacks.

2.1 Static channel assignment

The static assignment strategy assigns a channel to each interface permanently or for a long time. The benefit of this strategy is that there are neither the rendezvous problem nor the multi-channel hidden terminal problem, because each interface isn't switched among multiple channels. The related works of this strategy can further be classified into two categories. One is common channels method which assigns the same set of channels to the interfaces of each node [7, 8, 9]. Although the method can utilize multiple channels efficiently, it require as many interfaces as channels so that their hardware costs are very expensive. The other is diverse channels method which assigns the different sets of channels [16] to the interfaces of each node. This method may cause the network partition and isn't flexible.

2.2 Dynamic channel assignment

The dynamic assignment strategy allows each interface to be switched among multiple channels. The characteristic of this strategy is to utilize multiple channels with few interfaces. It is always used by the protocols, such as [1, 2, 3, 4, 5], which equip each host with one interface. Although it can save hardware costs and power consumption, solving the rendezvous problem and the multi-channel hidden terminal problem would be more difficult so that it must make some sacrifices, such as the utilization of channels and interfaces. The related works of this strategy use the time synchronization scheme to solve this two problems, but this scheme can't operate accurately in multi-hop environment.

2.3 Hybrid channel assignment

In recent years, the hybrid channel assignment strategy is proposed to improve the above two strategies. It equips each host with few interfaces and doesn't need the time synchronization scheme. The strategy combines both static and dynamic assignment strategy. Some interfaces of a host use static assignment strategy and other interfaces use dynamic assignment strategy. It employs the static assignment to solve the rendezvous problem to let neighbors be able to find each other and employs the dynamic assignment to utilize multiple channels efficiently. The related works can be further classified into two categories. One is common channel static assignment method and the other is diverse channels static assignment method. They will be discussed below.

2.3.1 Common channel static assignment method

This method divides all available channels into a separate control channel and multiple data channels, and divide two interfaces into one control interface and one data interface. Every host assigns the control channel to its control interface permanently and switches data interface among all data channels. During every communication, the control interface is used to exchange control packets on the control channel in order to obtain rights to access data channels and the data interface is dynamically switched to the selected data channel to do data transmission. The used data channel must be reserved before on the control channel, so they can resolve traffic contention on the data channels and avoid multi-channel hidden terminal problem.

DCA (Dynamic Channel Assignment) [10] and DCA-PC (Dynamic Channel Assignment with Power Control) [11] are the related works of this method. In DCA protocol, each mobile host maintains two data structures as CUL (channel usage list) which contains the list of busy channels and FCL (free channel list) which contains the list of idle channels. The main idea of DCA is that the sender A sends an RTS with FCL to the receiver B. Then B compares this FCL with its CUL to select an idle channel for their subsequent communication and reply a CTS packet back. After receiving B's CTS packet, A will send a RES packet to reserve the selected channel in its neighborhood. After that, A and B will switch their data interfaces together to the selected channel and start data transmission. In DCA-PC protocol, it integrates the concept of power control into the DCA protocol. It sends control packets with maximum power and sends data packets with the receiver's specified power level which is determined by the receiving power level of control packets so as to exploit channel reuse.

There are three main drawbacks of this method. First, the control channel will be a bottleneck when the number of data channels is large. Second, the channel utilization will be low when the number of orthogonal channels is small, because there must be a channel to be the control channel so that the proportion of the available capacity to the overall bandwidth is only two-thirds. Third, the utilization of interfaces is only half, because the control interface can't be used to transmit data packets.

2.3.2 Diverse channels static assignment method

This method equips each host with one fixed interface and one switchable interface. Every host assigned a channel to its fixed interface permanently or for a long time and this channel of each host can be different. The switchable interface can be switched among all channels. If the sender wants to communicate with the receiver, it will switch its switchable interface to the channel where the receiver's fixed interface is. It can solve rendezvous problem easily and doesn't need a time synchronization scheme or a separate control channel to do coordination. The following are the related works belonging to this method.

Pathmasuntharam et al. [13] introduced PCAM (Primary Channel Assignment based MAC) which employs three interfaces and use modified transmission range threshold to solve the multi-channel hidden terminal problem. The primary and secondary interfaces are respectively fixed and switchable interfaces, and the tertiary is used for broadcast messages. It reduces the effective transmission rage to let the neighbors of each fixed interface doing transmission know the interface is busy. There are two main drawbacks of this scheme. First, using physical carrier sensing function and the adjustment of transmission range to solve the hidden terminal problem can't operate accurately in real environment, because the power which is affected by many factors is instable in real condition. Second, whether to switch a switchable interface to a new channel is decided by per packet, so the overhead is great.

Kyasanur et al. [14] proposed a suite of routing and link-layer protocols for multiple channels called HMCP (Hybrid Multi-Channel Protcol). The proposed protocol in this paper is based on the MAC protocol of HMCP. We will introduce its MAC protocol in detail below.

It equips each host with two half-duplex transceivers.

One interface is called fixed interface and the other is called switchable interface. They will be specified as follows.

1. Fixed Interface: This interface is assigned a channel statically and stays on the assigned channel called fixed channel for a long time interval. It is mainly used to avoid the rendezvous problem. It ensures that a node intending to communicate with its neighbors can switch to their fixed channels to communicate with their fixed interfaces.

2. Switchable Interface: This interface can be switched dynamically among multiple channels except the fixed channel. These channels are called switchable channels. The interface is mainly used to utilize multiple channels and ensure network connectivity by switching to others' fixed channels to do communication.

These two interfaces operate independently, so they can depend on their own demands to do transmission and don't have overhead on coordination. Furthermore, each node gathers the information of its neighbors' fixed channels through broadcast messages and knows where to find them, so this scheme doesn't require a separate control channel or the time synchronization scheme. Figure 2 illustrates the possible communication scenarios. Assume the fixed channel of host A is assigned channel 1. If A wants to communicate with the hosts, as B and C, which are assigned different fixed channel, A would switch its switchable interface to their fixed channels to communicate with their fixed interfaces. If the other hosts, as D, are assigned the same fixed channel as A, A would use its fixed interface to communicate with their fixed interfaces.

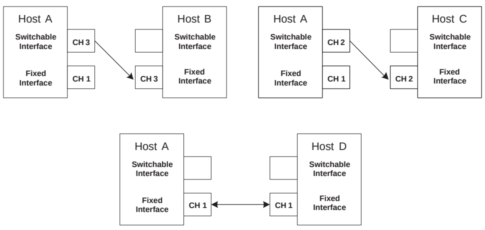

Figure 2: The possible communication scenarios.

In order to reduce the overhead of interface switching delay, the protocol equips each host with multiple queues as many as channels. Each queue is related to a channel and keeps the packets transmitted on this channel. The scheme puts a packet into the related queue by the fixed channel of its receiver. Therefore, each host can decide to switch its switchable interface to a new channel by the condition of queues, not by the destination of each packet. If whether to switch the switchable interface is decided by each packet, it may be switched frequently and the overhead is great because the objective channels of adjacent packets may be always different. This method can reduce the overhead of the interface switching delay by forcing each switchable interface to stay on each switchable channel for a period to transmit many packets.

The staying period of a switchable interface on each switchable channel must be carefully defined. Using a small value of this period increases switching overhead, while using a too large value causes starvation of other switchable channels and results in more end-to-end delay. A switchable interface can only stay on each channel for the length of the MaxSwitchTime duration at most and is always switched to the channel with the oldest queued packets. It is switched to a new channel only when the queues of other switchable channels are not empty and one of the following two conditions holds:

1. The queue of the current switchable channel is empty.

2. The switchable interface has been on the current channel for more than the MaxSwitchTime duration.

Each host has a virtual NAV for each channel. When a host switches its interface to a new channel, its NAV for this channel may not be correct because of the multi-channel hidden terminal problem. In order to avoid this problem, each host must be idle for the WaitingTime duration to update its NAV. The length of WaitingTime is defined as the transmission time of one maximum size packet.

There are two drawbacks of this protocol. First, the length of MaxSwitchTime is fixed, but the traffic loads of all channels for each host are usually different and vary with time. Second, the length of WaitingTime is too long so as to decrease the utilization of switchable interfaces. In this paper, the proposed protocol is based on this hybrid channel assignment approach and introduces two methods to solve the above two problems.

3 The proposed MAC protocol: HMCMP

The proposed MAC protocol is called HMCMP (Hybrid Multi-Channel MAC Protocol). This is an improvement of the MAC protocol of HMCP [14]. It takes the fairness of resource distribution into consideration, and reduces the overhead of switching interfaces. We propose a dynamic MaxSwitchTime assignment strategy to dynamically adapt the MaxSwitchTime to the traffic loads of each channel and a dynamic WaitingTime assignment to dynamically define the length of each host's WaitingTime on each channel depending on the condition of each channel. These two improvements will be detailed below.

3.1 Dynamic MaxSwitchTime assignment

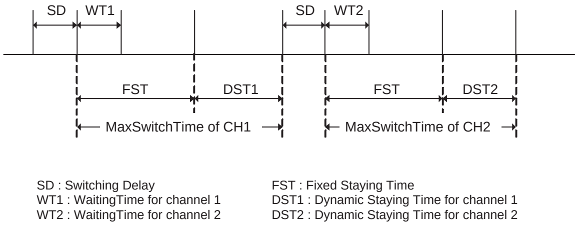

Figure 3: The MaxSwitchTime assignment.

We estimate the traffic loads of each channel for each host by the number of packets in the related queue. The more the number of packets a queue has, the more transmission time it requires. Each host derives the MaxSwitchTime of each switchable channel dynamically. We divide a MaxSwitchTime into a FST (Fixed Staying Time) period and a DST (Dynamic Staying Time) period. The values of all FSTs are assigned the same value. There is an overhead of an interface switching delay and a WaitingTime delay after switching to a new channel every time, so we restrict every host to stay on a channel for at least a FST period to ensure the utilization of switchable interfaces. However, the DST of each switchable channel for each host is assigned dynamically and is in proportion to the number of packets in the related queue. The DST of each switchable channel is defined to be:

$$DST_i = \frac{X_i}{\sum_{j=1}^{N} X_j} \times SDST \qquad (1)$$

where DST_i is represented as the DST of switchable channel i, X_i is the number of packets in the queue of switchable channel i, N is the number of switchable channels and SDST is the sum of all switchable channels' DSTs of a host. The SDST of each host is still dynamic and is decided by the number of the queued packets of a host. For example, although the proportions of the number of packets 30 and 10, and 9 and 3 are the same, the required transmission time of these two conditions must be different. We define a value MSDST (Maximum SDST) which is represented the maximum of SDST. When the queues of all switchable channels of a host are full, the value of SDST is MSDST. The SDST which is derived by the proportion of the sum of the number of packets in all queues to the total capacity of all queues is defined to be:

$$SDST = \frac{\sum_{j=1}^{N} X_j}{C} \times MSDST \qquad (2)$$

where X_j is the number of packets in the queue of switchable channel i, N is the number of switchable channels and C is the total capacity of all queues of switchable channels. After a switchable interface of a host switches around all switchable channels, the host has to re-compute the DST of each switchable channel every time.

3.2 Dynamic WaitingTime assignment

We consider that the length of WaitingTime equal to the transmission time of one maximum size packet is too long to sacrifice some utilization of switchable interfaces. Nonetheless, that the length of WaitingTime is too short would cause more collision occurrence. We will find the value of WaitingTime which is the equilibrium of interface utilization and collision occurrence. However, how long the value of WaitingTime set is related to the probability of collision occurrence. If the probability of collision occurrence for a switchable interface on some channel is low, this interface only needs a shorter value of WaitingTime on this channel. On the contrary, it would need a longer value of WaitingTime to avoid the high probability of collision occurrence.

The collision always occurs in the following scenario. Host A switches to a new channel where there is a transmission in progress and the sender B is sending a CTS packet or a data packet to the receiver C. Host A can't hear the packets from B but it is in the transmission range of C. Thence, A can't know this ongoing transmission if it doesn't receive the complete CTS packet to update its NAV. For avoiding this kind of collision occurrence, A only needs to consider its neighbors, such as host C whose fixed channel is the same as the new channel, because only the fixed interface is used to receive data. That is, the collision always happens on fixed interfaces. Therefore, we can estimate the collision probability for a host on some channel by the number of neighbors' fixed interfaces on this channel. More the number of neighbors' fixed interfaces a host has on some channel, Longer the length of WaitingTime it should use to avoid more the probability of collision occurrence.

We use simulations to find the best values of WaitingTime for various number of neighbors' fixed interfaces. Figure 4 is the aggregate throughput of various WaitingTime for one, two and three neighbors' fixed interfaces. We can get a suite of the best WaitingTime (Table 1) and adopt these values in our proposed protocol. Moreover, we can know that the long length of WaitingTime has the worse performance from figure 4. Modeling the relation of WaitingTime and interface utilization to find every best WaitingTime from calculation is part of our future work.

4 Simulate results

In this section, we compare the performance of the proposed MAC protocol with that of HMCP [14] and IEEE 802.11 MAC protocol in ns-2 [17]. The duration of each simulation is 120 seconds. The basic rate is 1 Mbps

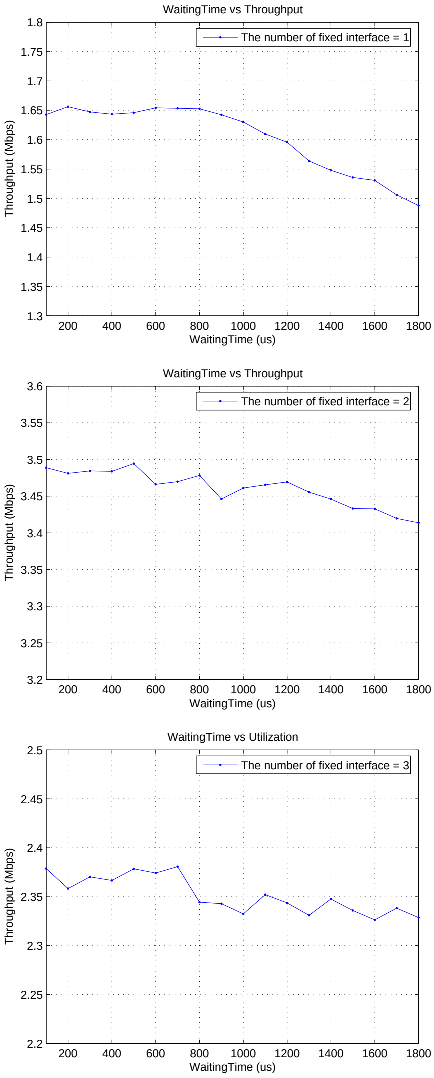

Figure 4: The aggregate throughput of various WaitingTimes when the number of neighbors' fixed interfaces is one, two and three.

and the data rate is 11 Mbps. All nodes are assumed to be stationary and their transmission ranges are 250m. The packet size is fixed at 1024 bytes. The number of channels is three and the interface switching delay is assumed to be 1ms. The FST and MSDST are assigned 4ms and 10ms respectively. These two values are chosen by the experiment and the performance of using these two values is good. We only consider the CBR (Constant Bit Rate) traffic and make the packet arrival rate varied to simulate the various offered loads.

4.1 Chain topology

We discuss the topology of a chain first. There are six nodes in a chain and the neighbors are away from each

Table 1: The suite of the best WaitingTime.

The number of fixed interfaces	WaitingTime(us)
1	200
2	500
3	700

other at a distance of 200m. The aim of this experiment is to study the aggregate throughput and the average end-to-end delay in a multi-hop network. There are two traffic flows applied to this topology. One flow is from node 1 to node 6 and the other is reverse. The fixed channel assignment used in this experiment is $\{1,2,3,1,2,3\}$. This kind of traffic can produce much of the occurrence of multi-channel hidden terminal problem and the unbalanced loads of each channel.

Figure 5 and 6 show respectively the aggregate throughput and the average end-to-end delay. The hybrid MAC protocols utilizing multiple channels efficiently can improve the original IEEE 802.11 MAC protocol greatly. The average end-to-end delay of IEEE 802.11 MAC protocol is much larger than that of the hybrid MAC protocols, so we don't compare it in the figures. When the traffic loads are heavy, the effect is more evident. The performances of the aggregate throughput and the average delay in HMCMP outperform that in HMCP by more than 10 percents under heavy load condition since the proposed dynamic MaxSwitchTime assignment can adapt the transmission time to the traffic loads under the condition of unbalanced loads and the proposed dynamic WaitingTime assignment can improve the utilization of interfaces.

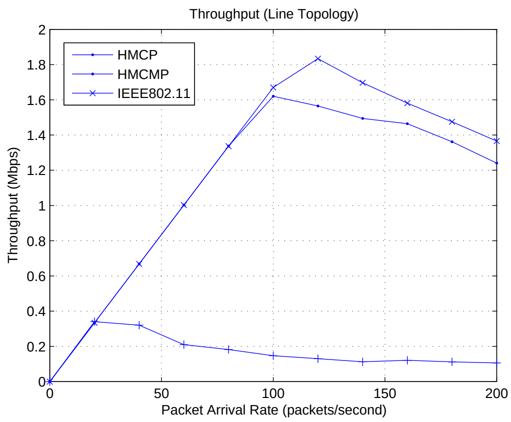

Figure 5: The aggregate throughput of a chain topology.

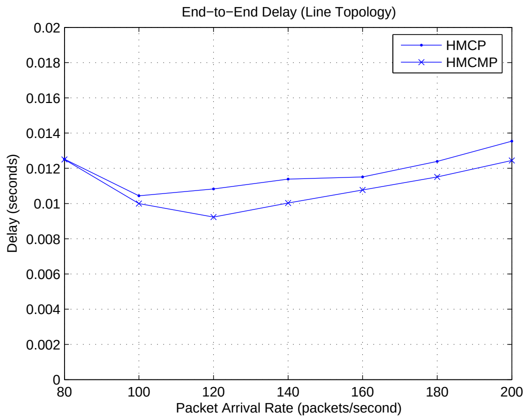

Figure 6: The average end-to-end delay of a chain topology.

4.2 Grid topology

In this section, we study the performance of the protocols in a multi-hop ad-hoc network. There are three sizes of grids, respectively a 3 by 3 grid, a 6 by 6 grid and a 9 by 9 grid. The distance between adjacent nodes is 150 m. There are respectively 12, 24 and 36 traffic flows and respectively 3, 6 and 9 flows from each side of the grids to its opposite side. Three channels are assigned evenly to all fixed interfaces.

Figure 7 show the aggregate throughput and figure 9 show the average end-to-end delay. The hybrid protocols still have great performances over the IEEE 802.11 MAC protocol. In hybrid protocols, the performances in HMCMP also outperform that in HMCP, but the improvement of grid topology isn't as great as that of the chain topology, the 9 by 9 grid topology especially. With the increasing of the grid size, the performances of the proposed protocol worsen. This is because using a long length of Waiting-Time alleviates the severe contention of the network in a different form.

5 Conclusion

In this paper, we propose a new multi-channel MAC protocol HMCMP to improve the unbalanced allocation of resources and the utilization of both channels and interfaces in HMCP. We use a dynamic MaxSwitchTime assignment scheme to dynamically adapt the transmission time to the varied traffic loads and a dynamic Waitint-Time assignment scheme to improve the utilization of interfaces. We have compared the performance of the proposed protocol with that of HMCP and IEEE 802.11 MAC protocol. The results show that our improvements work well and the hybrid MAC protocols with utilizing multiple channels efficiently have great performances over IEEE 802.11 MAC protocol.

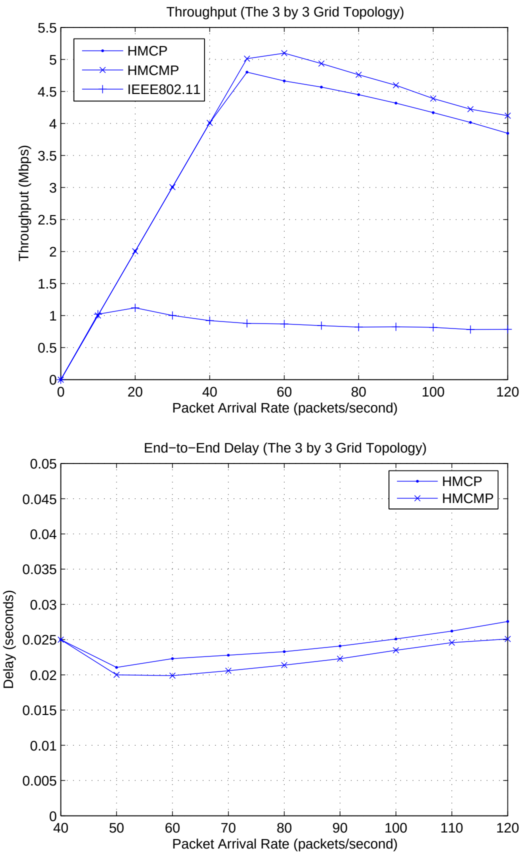

Figure 7: The aggregate throughput and the average end-to-end delay of a 3 by 3 grid topology.

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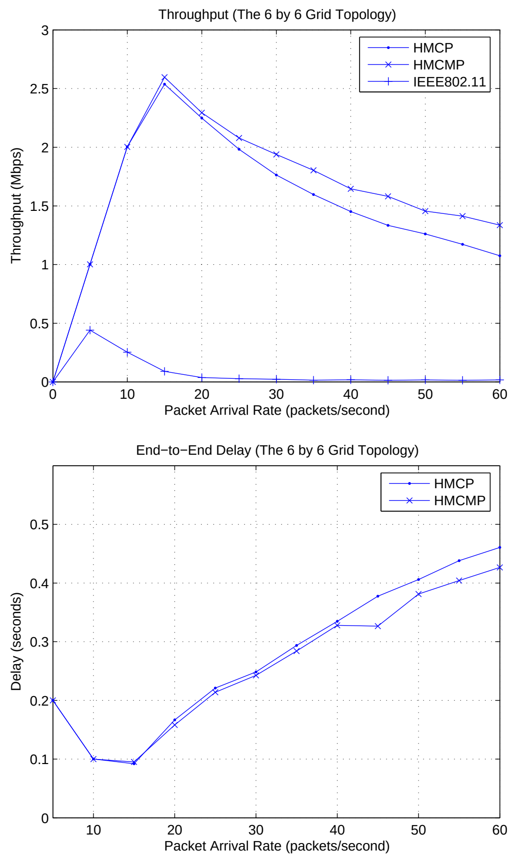

Figure 8: The aggregate throughput and the average end-to-end delay of a 6 by 6 grid topology.

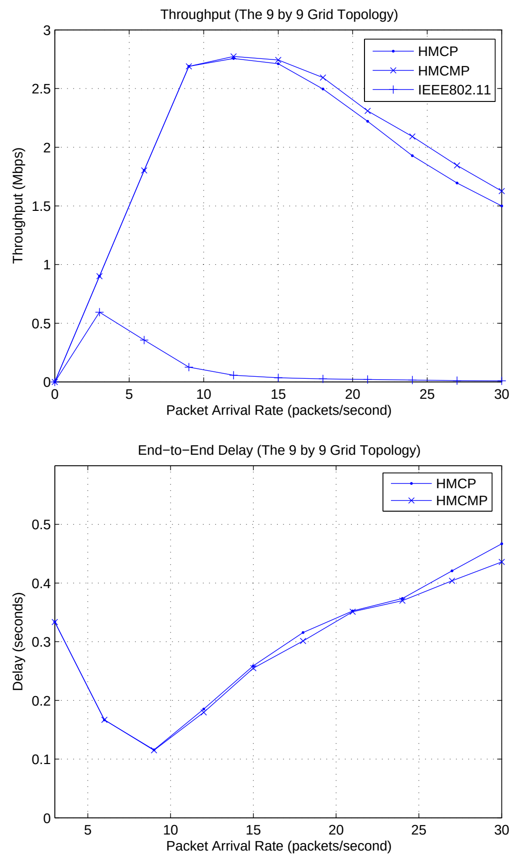

Figure 9: The aggregate throughput and the average end-to-end delay of a 9 by 9 grid topology.

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