A Collision Avoidance Multi-Channel MAC Protocol with Physical Carrier Sensing for Mobile Ad Hoc Networks

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***Abstract*— Carrier sensing mechanism has been adopted in IEEE 802.11 MAC for collision avoidance under single channel based wireless ad hoc networks. However, due to the hardware limitation, the carrier sensing mechanism can not help much in single transceiver and multi-channel scenarios. In this paper, we propose a pipelining multi-channel (π-Mc) MAC protocol for multi-channel ad hoc networks. The core idea of π-Mc is similar to the pipeline technique. Without collecting each channel usage information, π-Mc not only uses overall channel resources for transmission, but also can prevent DATA collisions. The performance of π-Mc is compared with two well-known multi-channel MAC protocols and IEEE 802.11 DCF. Simulation results show that π-Mc is able to achieve 2.50 times the throughput of IEEE 802.11 DCF, as well as respectively outperform DCA and MMAC with a factor of up to 1.43 and 1.32 under three available channels.**

I. INTRODUCTION

A wireless ad hoc network is a network temporarily formed by a collection of stations (STAs) without relying on any established infrastructure. Collision is the major factor to decrease the network performance. In particular, hidden terminal problem is a notorious collision problem. IEEE 802.11 DCF [1] has been the most popular MAC protocol for STAs to contend the shared medium in wireless ad hoc networks. Two well-known functions, physical and virtual carrier sensing mechanisms, are adopted prior to DATA transmission in IEEE 802.11 MAC to avoid hidden terminal problem.

On the other hand, due to the medium bandwidth limitation, the network performance will get a bottle threshold [2] when the traffic increases. Fortunately, IEEE 802.11 standard provides multiple channels for transmission such as three non-overlapped channels in IEEE 802.11b [3], and 12 non-overlapped channels in IEEE 802.11a [4], respectively. As a result, a simple and efficient solution to improve the network performance is to balance the load on all the available channels.

Unfortunately, due to the hardware limitation, the number of transceivers within a STA is usually less than the number of available channels. In fact, IEEE 802.11 device is only equipped with single half-duplex transceiver. Therefore, carrier sensing technique can not work well to set the medium state (idle or busy) for multi-channel scenario and to prevent the hidden terminal problem. Specifically, a multi-channel hidden terminal problem is described later. Therefore, a lot of researches pay their attention on how to collect channel usage information under the limited number of the transceivers as follows are classified into three categories.

- ***Channel separation scheme***
  The concept of channel separation is that an individual channel is used for channel negotiation among all STAs [5]–[9]. Two transceivers are also needed. The first transceiver is switched to dedicated channel, and the other can be tuned to any other channels for DATA transmission. Therefore, each STA is able to get the channel usage information, and decides a free channel for DATA transmission anytime without any collisions. Because of two transceivers needed, channel separation scheme are not practical.
- ***Time split scheme***
  Time is divided into many beacon intervals for the time split scheme [10]–[15]. Each beacon interval includes two phases, such as ATIM window and DATA exchange phases. During the ATIM window phase, all STAs switch their transceivers to a common channel for channel negotiation and reserve free channels for transmission. Next, at DATA exchange phase, STAs send DATA in the previous contending channel concurrently. Incidentally, time split scheme requires synchronization, which is a difficult work and cannot able to apply to multi-hop environment.
- ***Cooperation coordination scheme***
  All the available channels are classified to a control channel and DATA channels in the cooperation coordination scheme [16]–[19]. The node in idle state switches the transceiver to the control channel for collecting channel usage information. In DATA transmission, the node will tune to the free DATA channel for transmission. Accordingly, the node will miss the channel usage information due to the single transceiver constraint. In the cooperation coordination scheme, if a node have the correct channel information and is in idle state, it will update the channel knowledge for neighbors. Note that the cooperation coordination scheme can not prevent collision completely because the collected channel information is incorrect.

Additional transceiver or time period are necessary for the above mentioned schemes to obtain the channel usage information. Even the collected information is not correct. Hence, a pipelining multi-channel MAC protocol, named π-Mc, is proposed for multi-channel ad hoc networks. The main idea of π-Mc is similar to pipeline technique. Without collecting all the channel usage information, π-Mc not only can prevent DATA collisions to decrease the packet loss rate, but also uses all channel resources for transmission to increase network throughput if a STA firstly contends medium successfully. The performance of π-Mc is compared with two well-known multi-channel MAC protocols, DCA [5] and MMAC [10], and IEEE 802.11 DCF mechanism. Simulation results show that π-Mc outperforms DCA and MMAC under three available channels.

The rest of this paper is organized as follows. Section II makes two examples to describe the hidden terminal problem induced in multi-channel environment. In addition, the core principle of π-Mc is also stated in Section II. Some problems are still in π-Mc. Consequently, π-Mc is formulated and analyzed under the different DATA sizes in Section III. Simulation results are presented in Section IV. Section V concludes the paper.

II. Preliminaries

Two cases are analyzed in this section to support the reason that the carrier sensing mechanism can not work well to avoid hidden terminal problem for multi-channel wireless ad hoc network. Further, the brief solution termed π-Mc for hidden terminal problem is also introduced in this section.

A. *Multi-channel environment induced hidden terminal problem*

Carrier sensing mechanism can not perform well in multi-channel environment because the STA are not able to obtain all the channel usage information with the single transceiver. In this section, two cases are briefly analyzed and discussed to the hidden terminal problem in multi-channel environment.

- **Control packet missed**
  Consider the scenario in Fig. 1(a). Suppose two transmission pairs, A to B and D to E, are in the network. Unfortunately, C will miss information about B and D because it listens to the different channels as B and D. C is likely to choose an unsuitable channel for transmission such as the channel used by B or D. Therefore, the hidden terminal problem will happen due to STA missing control information.
- **Control packet collided**
  Another case is shown in Fig. 1(b). All STAs stay on the same channel. However, if B and D respectively exchange control messages at the same time or within an overlapping period, C is unable to be aware of the channel usage information of B and D. As a result, C is likely to choose the same channel as D or B to transmit. Hence, the collision will happen because of control packet collided.

B. *The concept of π-Mc*

As discussed in Section II-A, the hidden terminal problem will happen because the STA can not acquire all the channel usage information. In the section, a pipelining multi-channel MAC protocol called π-Mc is proposed for collision avoidance. The concept of π-Mc is similar to pipeline

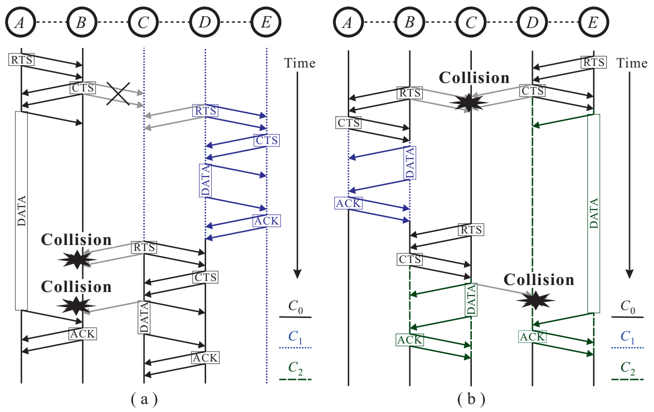

Fig. 1. Multi-channel hidden terminal problem happens because STAs exchange control packet on (a) the same channel, and (b) the different channels.

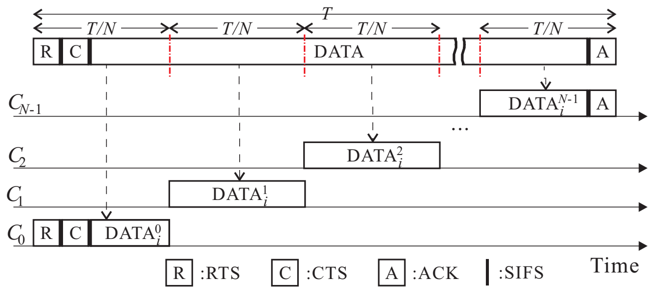

Fig. 2. The concept of π-Mc. The total transmission of a DATA packet is divided into N fragments which is the number of the available channels. Each fragment is transmitted on the corresponding channel.

technique. The transmission task will be divided into many subtasks. All of subtasks are transmitted on different channels sequentially. Therefore, if we can make sure that the first subtask is transmitted successful, all the other subtasks also succeed in transmission. Therefore, π-Mc is able to prevent hidden terminal problem without recording any channel usage information.

An example in Fig. 2 is used to illustrate π-Mc. Suppose N channels ($C_0 \sim C_{N-1}$) are available in the networks. A transmission is equally divided into N fragments. STAs based on the IEEE 802.11 DCF contend the access right on C_0. ACK is sent on C_{N-1}. All the other channels are only used to transmit DATA fragments sequentially. Note that C_0 and C_{N-1} may used for DATA transmission, if necessary. If STA has finished the first fragment transmission, C_0 will be released. The other STAs are able to compete C_0 for their transmission continuously. Actually, if the network is with a higher traffic, all the channels will be used for transmission. Therefore, we can get the purpose of parallel packet transmission at the same time, and upgrade the usage of channels.

It's worth mentioning that a STA should stay on C_0 for a fragment transmission period after previous transmission finishes. In this way, the previously mentioned hidden terminal problem can be more effectively avoided.

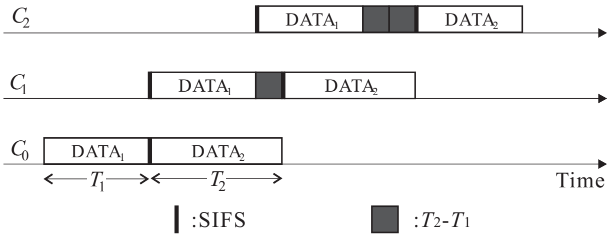

Fig. 3. The concept of channel hole problem if $T_1 < T_2$.

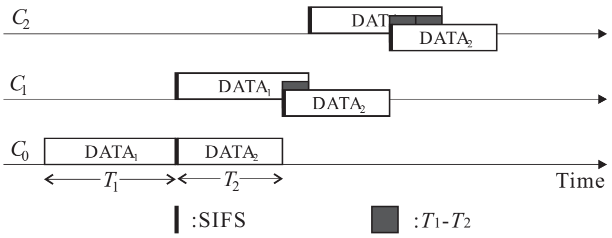

Fig. 4. The concept of frame collision problem, if $T_1 > T_2$.

III. The pipelining multi-channel MAC protocol(π-Mc)

In Section II-B, we have introduced the main idea of π-Mc. However, channel hole, frame collision, and channel leak problems will occur due to the different DATA size. Therefore, the discussion for π-Mc with the different DATA sizes is presented in this section. Finally, in order to improve the access delay time, a modification is also proposed for π-Mc.

A. The impact of the different DATA sizes

Each transmission has a higher probability with the different sizes in wireless ad hoc networks. Suppose T_1 and T_2 are the transmission times of $DATA_1$ and $DATA_2$, respectively. Three cases and three problems will occur and are illustrated as follows.

- $T_1 < T_2$
  The case about $T_2 > T_1$ appears in Fig. 3. Channel hole is in existence on C_1 and C_2. Due to the different DATA packet size, $DATA_2$ is still transmitted on C_0 when $DATA_1$ has finished the transmission on C_1. Therefore, the size of the channel hole on C_1 is T_2 - T_1. As the result, we can conclude the total bandwidth wastage as
$$\sum_{k=1}^{N}(k-1)(T_2-T_1) = \frac{N^2-N}{2}(T_2-T_1). \quad (1)$$
- $T_1 > T_2$
  Anther case for $T_2 < T_1$ is illustrated in Fig. 4. As $DATA_2$ has been over its transmission on C_0, $DATA_1$ is still in transmission on C_1. At this moment, if $DATA_2$ switches to C_1 for transmission, the frame collision will take place.
- $T_1 = T_2$
  Two packet with the same transmission time is the third situation. If $DATA_2$ has finished the transmission on C_0, $DATA_1$has also completed the transmission on C_1. As shown in Fig. 5, channel hole and frame collision problem will not occur. Therefore, our π-Mc protocol will operate very well when all the DATA sizes are equal.

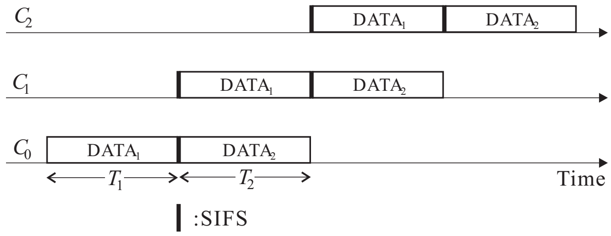

Fig. 5. The best case for π-Mc without channel hole and frame collision problems.

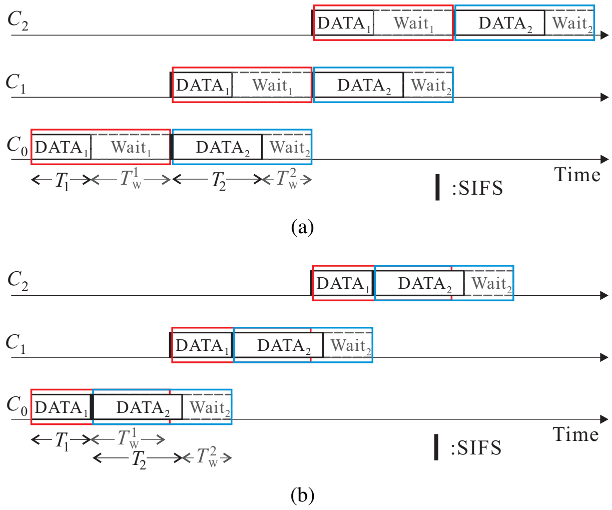

Fig. 6. The scheme to reduce the access delay in π-Mc.

According to the previous discussion, π-Mc protocol will operate well in equal DATA size scenario. However, it is almost impossible that each transmission is with the same DATA size. We can conclude that π-Mc would adopt the maximum DATA size to calculate the duration of the transceiver on each channel for channel hole and frame collision avoidance,.

B. Extension for delay issue

π-Mc adopts the maximum DATA size to evaluate the duration of each channel. In fact, if the DATA is not with the maximum size, as shown in Fig. 6(a), π-Mc is in the existence of another bandwidth wastage problem which is called channel leak problem. The solution for channel leak problem appears in Fig. 6(b). Therefore, in order to solve the channel leak problem, the next DATA can transmit early when the previous STA has finished its DATA transmission on C_0. The transmission delay can be improved significantly.

IV. Performance Evaluation

In this section, we evaluate the performance of the proposed protocol by simulation. The simulation is implemented in ns–2 simulator [20]. The bandwidth of each channel is 1Mbps, and three channels are available. The transmission range and carrier sensing range are 250m and 550m respectively in all protocols. The other parameters are shown in Table I. We

TABLE I

SIMULATION SETTINGS.

Parameter	Value
The number of available Channels	3
Source Traffic	Exponential Traffic
Transmission rate	1Mb/s
Frame length	1500 Bytes
Channel Switch Time	1μs
Simulation time	10 sec.

compare our protocol with IEEE 802.11 DCF mechanism [1], and well-known multi-channel MAC protocols include DCA and MMAC on the same simulation platform. Recall that DCA protocol uses a dedicated control channel for exchanging control messages and the other channels for data transmissions. Moreover, MMAC protocol uses a special separate ATIM window for negotiating channel selection on a common default channel. STAs transmit data in the following data window based on the channel negotiation results. We use two metrics to evaluate the performance.

1. *Aggregate Throughput*
   π-Mc is expected to increase the overall throughput under multiple available channels. The ideal aggregate throughput is N times of the single channel given that N channels are available. Our protocol can be closest to the ideal line because our protocol dose not need any additional overhead of resource in time-domain or channel-domain. However, the ideal throughput can not be achieved due to the overhead required for data packet fragmentation.
2. *Average Delay*
   Average delay is the time duration between the time when sender receives a packet from link layer, and the time of destination receives the packet from sender.

Fig. 7 illustrates the network throughput of the proposed π-Mc against IEEE 802.11 DCF, DCA and MMAC in terms of packet arrival rate varied from 1 packet per second to 20 packets per second. Due to the design for single channel and single transceiver, when the packet arrival rate reaches to eight packets per second, the network throughput is saturated to 0.8Mbps. Therefore, the network throughput keeps stable when the packet arrival rate more than eight. However, multiple channels are available for π-Mc, DCA and MMAC protocols. Therefore, the network throughput of DCA and MMAC are almost twice of IEEE 802.11 DCF, π-Mc protocol almost reaches triple of IEEE 802.11 DCF especially.

By using a special dedicated control channel to exchange the control message and by adopting the special separate ATIM window for negotiation the channel selection respectively, the throughput of DCA and MMAC will get saturated since the packet arrival rate reaches 15 and 17 packets per second. Therefore, the network throughput of DCA and MMAC are 1.5Mbps and 1.6Mbps respectively. It is because that DCA wastes bandwidth of control channel and MMAC wastes bandwidth of all channels expect default channel in ATIM window. Furthermore, the improvement of throughput only achieve 187.5% and 200% compare with IEEE 802.11 DCF.

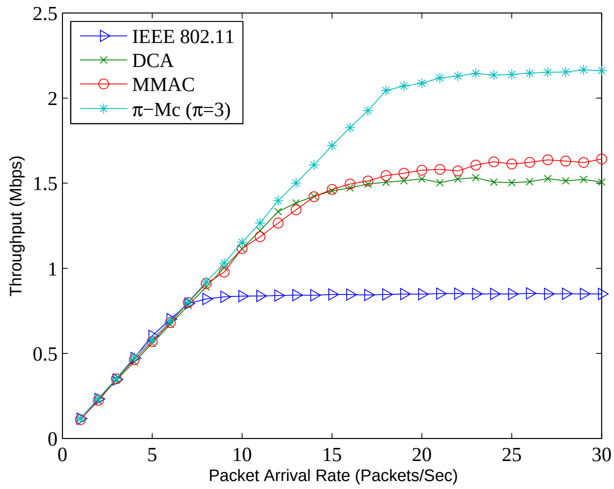

Fig. 7. The comparisons of throughput for π-Mc, DCA, MMAC and IEEE 802.11 DCF to different traffic load.

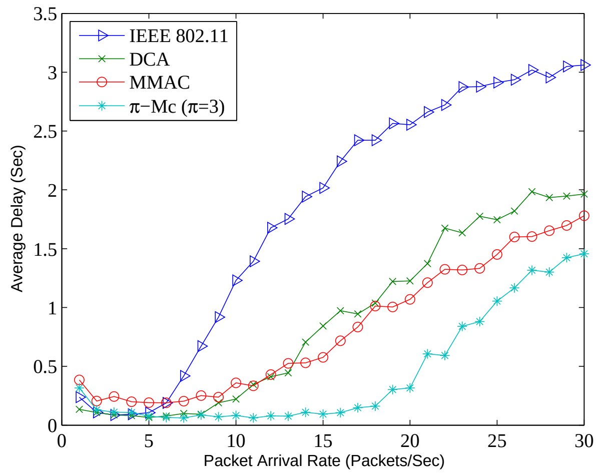

Fig. 8. The comparisons of average delay for π-Mc, DCA, MMAC and IEEE 802.11 DCF to different traffic load.

However, all channels are always used for DATA transmissions in π-Mc. Therefore, the maximum network throughput of π-Mc is able to increase to 2.2Mbps, and the improvement of throughput is 275%. Moreover, the effect of improvement of π-Mc outperforms 87.5% and 75% compared with DCA and MMAC respectively.

We also observe the average delay of π-Mc, IEEE 802.11 DCF, DCA and MMAC protocols since STAs have different packet arrival rate. In Fig. 8, we can see that the packet delay is hold, and all the transmission is finished within 0.2 seconds since the network throughput is not saturated in Fig. 7. However, when the network throughput is saturated, some packets will be queued in STAs. Thus, the average delay will dramatically increase. It is worth to mention that our proposed protocol allows more transmissions since the network is saturated. Consequently, π-Mc has the smallest average delay among all the compared MAC protocols.

Fig. 9 illustrates the network throughput of the proposed π-Mc against IEEE 802.11 DCF, DCA and MMAC multi-

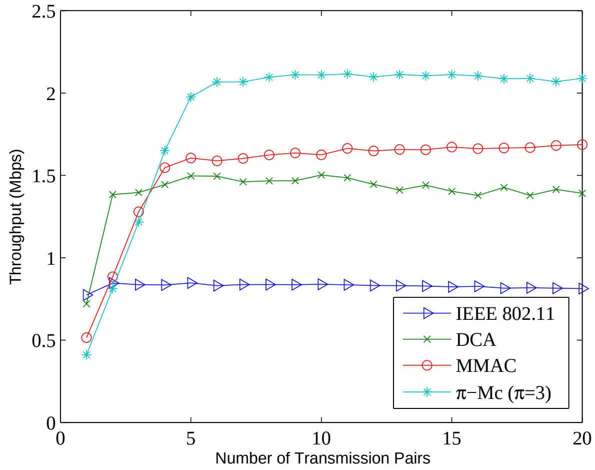

Fig. 9. The comparisons of throughput for π-Mc, DCA, MMAC and IEEE 802.11 DCF to different number of transmission pairs.

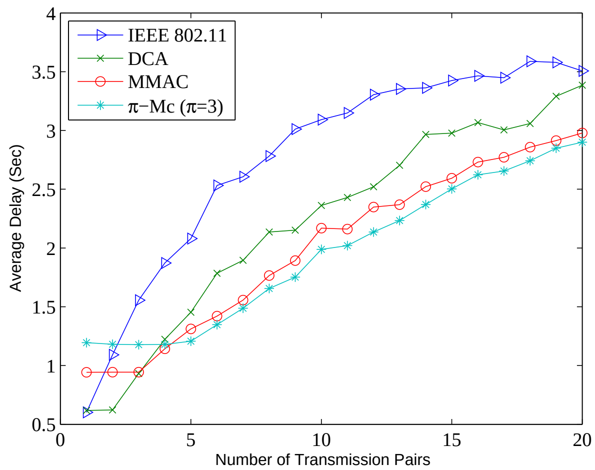

Fig. 10. The comparisons of average delay for π-Mc, DCA, MMAC and IEEE 802.11 DCF to different number of transmission pairs.

channel MAC protocol in terms of the number of transmission pairs varied from 1 pair to 20 pairs. Suppose all STAs always have packets to send. Due to single channel for IEEE 802.11, the throughput of DCF gets saturated since single transmission pair is within the network. Similarly, DCA uses one channel as a control channel to exchange control packets. Therefore, only two channels are for DATA transmission, and the throughput of DCA will achieve saturation since two transmission pairs are allowed in this network. Considering the network throughput of MMAC, it is able to achieve saturated since the number of transmission pairs increase to three pairs, and then keeps stable. Nevertheless, the resource are wasting in the separate ATIM window, it makes the aggregate throughput be unable to achieve the ideal value. However, the concept of pipeline mechanism is designed in π-Mc protocol that all channels are used for DATA transmission all the time. Hence π-Mc protocol can improve the network throughput efficiently by allowing more transmission pairs, and outperforms 260%-280% better than IEEE 802.11 MAC protocol. Furthermore, it is worth to mention that π-Mc can accommodate more transmission pairs actively.

Fig. 10 shows the result of average delay in the same scenario with Fig. 9. Similar to the situation of Fig. 8, π-Mc is still able to reach the lowest average delay. It is worth mentioning that π-Mc protocol will not perform well if only few transmission pairs are within the network. In order to avoid the multi-channel hidden terminal problem, transmitters must wait for a short period to re-contend medium after finishing one DATA transmission. So the π-Mc protocol will perform badly when the number of transmission pairs is less than the number of available channels. However, it can perform well when 5 transmission pairs and 3 channels are available in the network.

V. Conclusions

In this paper, we have proposed a pipelining multi-channel MAC protocol, named π-Mc, that utilizes the overall available channels to improve throughput and average delay for wireless ad hoc networks. π-Mc also can avoid multi-channel hidden terminal problem without any additional resource in time-domain or channel-domain. Hence π-Mc can reach the higher performance than other multi-channel MAC protocols. Channel hole problem, frame collision problem and channel leak problem are also discussed in π-Mc. Simulation results show that π-Mc successfully exploits multiple channels to improve total network throughput and performs the improvement 175%, 87.5% and 75% better than IEEE 802.11 DCF, DCA and MMAC protocols, respectively.

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