Multi-phased Carrier Sense Multiple Access with Collision Resolution

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Abstract. To improve the efficiency of carrier sense multiple access (CSMA)-based medium access control (MAC) protocol, CSMA with collision resolution (CSMA/CR) has been proposed. In the CSMA/CR protocol, a transmitting station can detect a collision by employing additional carrier sensing after the start of data transmission and resolve the next collision that might occur by broadcasting a jam signal during a collision detection (CD) period. By extending this original CSMA/CR protocol that uses a single CD phase, in this paper we propose a multi-phased CSMA/CR (MP-CSMA/CR) protocol that employs multiple CD phases. In the proposed MP-CSMA/CR protocol, colliding stations are filtered in each CD phase, and only surviving stations compete again in the next CD phase. Therefore, the collision resolution probability becomes higher as the CD phases proceed. Results show that the proposed MP-CSMA/CR protocol significantly outperforms the conventional CSMA/CR with a single CD phase.

Keywords: Carrier sense multiple access (CSMA) · Medium access control (MAC) · Collision detection · Collision resolution

1 Introduction

One of the most performance-effective factors in a distributed wireless network is the medium access control (MAC) protocol, which decides how to efficiently distribute the limited radio resources among users while ensuring fair treatment of all users. A representative distributed MAC protocol in the distributed network is the carrier sensing multiple access with collision avoidance (CSMA/CA) protocol, which is widely used because of its operational simplicity [1]. However, it is well known that the efficiency of CSMA/CA is reduced by the successive collisions of retransmitted data as the number of contending stations increases [2]. To improve the efficiency of CSMA-based MAC protocols, the CSMA with collision detection (CSMA/CD)-like behavior has been variously emulated in wireless environments [3–7]. This attempt is due to the fact that CSMA/CD makes it possible for the transmitter to detect a collision while sending data and to suspend the transmission immediately when a collision is detected. However,

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the original CSMA/CD protocol is infeasible in wireless media because the wireless transmitter cannot send and listen at the same time on the same channel. If so, the receiver of the transmitter is overwhelmed by its own transmission power, which is called the deafness problem in wireless media.

As the first attempt to overcome the deafness problem and allow the CSMA/CD operation in a wireless network, CSMA with time-split collision detection has been proposed under assuming a long propagation delay [3]. In this protocol, the transmitter stops after sending a preamble with a fixed length and shortly performs carrier sensing. Because of the discriminating radio propagation delay, simultaneously transmitting stations can detect the other preamble signals and thus pause their data transmissions. For a shorter delay environment, CSMA with time-split collision detection based on multi-tone tree search has been proposed as well [4]. As more practical approach to collision detection in wireless media, a wireless CSMA/CD (WCSMA/CD) protocol has been presented [5,6]. In WCSMA/CD, every station defines a collision detection (CD) period with the same length and each transmitter randomly decides a short CD slot during the CD period after the data transmission starts. Then, the transmitter senses the channel at the selected CD slot to verify whether a collision has happened. If colliding stations exists and they all do not select the same CD slot, each station detects an energy level higher than the threshold at the CD slot; thus detecting a collision. In this case, the colliding stations abort their transmission within the CD period and thus the wasted time is reduced. By enhancing the WCSMA/CD, the CSMA with collision resolution (CSMA/CR) protocol has also been proposed [7]. Upon detecting a collision in CSMA/CR, the transmitter instantly stops its transmission and broadcasts a jam signal in order to notice the other stations that they must abort their transmissions. The CSMA/CR protocol gives a priority to the station that has sent the jam signal during the CD period to retransmit the data without backoff and makes the other stations defer access automatically. Consequently, this operation resolves a next collision that might occur and so leads to more performance improvement.

Although the previous CSMA/CR improves the MAC efficiency considerably, the access collision still exists and the throughput degrades due to the collision, backoff time, and additional protocol overhead. These problem become severer particularly when the number of accessing stations increases significantly [8]. In this paper, by extending the original CSMA/CR protocol [7], we propose a multi-phased CSMA/CR (MP-CSMA/CR) that employs multiple CD periods in order to further increase the probability of collision resolution and therefore increase the throughput. We investigate optimal operating parameters, such as the number of CD phases and the number of CD slots per phase, to maximize the throughput.

The rest of this paper is organized as follows. Section 2 reviews the operation of the original CSMA/CR protocol. Section 3 explains the operation of the proposed MP-CSMA/CR protocol in detail. Section 4 shows the throughput of MP-CSMA/CR by considering various parameters. Finally, Sect. 5 presents the conclusions drawn in this study.

2 Original CSMA/CR Protocol

In the CSMA/CR protocol, every transmitter allocates a short CD slot randomly within a predetermined fixed CD period when the data transmission starts. Thereafter, it senses the channel at the selected CD slot to verify whether energy or jam signal or both are detected or not. This operation generates four events in CSMA/CR, as shown in Fig. 1.

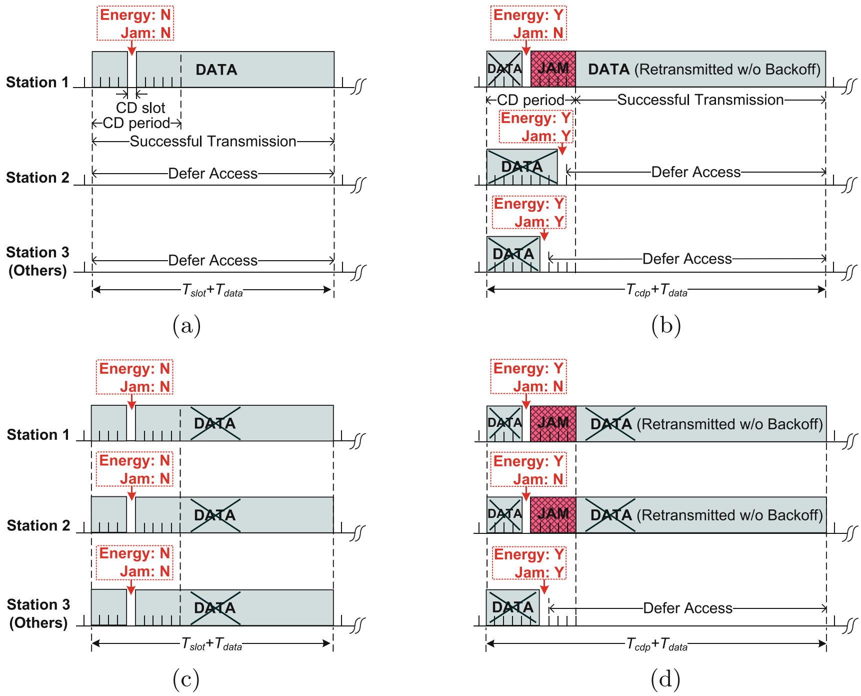

Fig. 1. Possible cases in CSMA/CR with a single phase; (a) 1st success: only one station accesses the channel, (b) 2nd success: collision is resolved as only one station chooses the earliest CD slot, (c) 1st failure: every station chooses the same CD slot, (d) 2nd failure: two or more (not all) stations choose the earliest CD slot.

Figure 1(a) illustrates the first success case in which any stations do not access simultaneously; therefore, neither energy nor jam is not sensed during the CD slot. The station keeps transmitting its data right after the short sensing at the CD slot and completes transmission successfully. Figure 1(b) shows the second success case in which Station 1, which chooses the earliest CD slot among the colliding stations, detects the energy but not a jam. Because Station 1 detects a collision first, it should subsequently transmits a jam signal instead of a data signal during the remainder of the CD period. This enables Stations 2 and 3 that select a later CD slot to detect both the energy and jam signal and their ongoing transmissions to abort immediately. At the end of the CD period, only the station that sent the jam signal is permitted to retransmit its data immediately without backoff whereas the other stations defer their access automatically. Such collision resolution protocol promises successful data retransmission of at least one station if a collision is detected during the CD period.

Figure 1(c) exhibits the first failure in which all colliding stations choose the same CD slot. Thus, they cannot detect the energy and thus continue data transmission, which cause transmission failure. The transmitter can recognize transmission failure by the lack of receipt of the acknowledgement (ACK) packet. Then, it retries to access after backoff. Figure 1(d) depicts another transmission failure when two or more stations (but not all) choose the earliest CD slot; therefore, the stations recognize only the energy, send the jam signal equally during the remaining CD period, and transmit the new data simultaneously. This also causes transmission failure.[1] Here, we denote the lengths of the CD slot, CD period, and transmitted data by T_{slot}, T_{cdp}, and T_{data}, respectively, and indicate the channel usage time in each case. Note that in the second success and failure cases, the wasted channel time is more than that in the first ones.

3 Proposed Multi-phased CSMA/CR Protocol

In the CSMA/CR protocol, collision can be resolved by one random slot selection in one CD period. However, there is still a chance of failure in collision resolution, as shown in Figs. 1(c) and (d). To decrease these failure probabilities, we try to repeat the CD period to provide more opportunities for random slot selection, thus utilizing the multiple CD phases. The operation of MP-CSMA/CR is described in following algorithm. As shown in Lines 7–20, in MP-CSMA/CR, the collision resolution process is repeated as many times as the predetermined number of CD phases (h).

Pseudo code of the proposed MP-CSMA/CR protocol

```
01: Sense the channel
02: IF (channel is idle & random[0,1] < p)
03:     Start data transmission
04: ELSE
05:     Wait until the channel is idle
06: ENDIF
07: FOR (i=0; i<h; i++)                     /* h = # of CD phases */
08:     Select a CD slot number=random[1,m] /* m = # of CD slots per phase */
09:     Pause at the selected CD slot and sense the channel
10:     SWITCH (sensing result)
11:         CASE (Energy=No & Jam=No):
12:             Continue data transmission
13:         CASE (Energy=Yes & Jam=No):
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[1] In this case, the station that selects the later CD slot (i.e., Station 3) detects the overlapped jam signal. Because an overlapped signal with the same pattern is generally detectable [9], Station 3 can recognize the jam signal and stop its transmission.

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            Transmit a jam signal until the current CD period ends
            Retransmit data from the beginning
        CASE (Energy=Yes & Jam=Yes):
            Stop data transmission
            Break and go to Line 21
    END SWITCH
END FOR
IF (Receive ACK)
    Transmission success
ELSE
    Transmission failure
    Execute backoff procedure
END IF
```

To explain the operation of MP-CSMA/CR in detail, we illustrate the possible event cases when only two CD phases are used. As shown in Fig. 2, there are three successful transmission cases and three failure cases. Figure 2(a) shows the case when only one station accesses the channel and no collision occurs. Figure 2(b) shows the case when only one station chooses the earliest CD slot at the first CD phase, and collision resolution is successful at the first CD phase. Figure 2(c) shows the case when collision resolution fails as two stations of the total three stations choose the earliest CD slot at the first CD phase. However, at the second CD phase, these two colliding stations continue the collision resolution process and only one station among them chooses the earliest CD slot and eventually collision is resolved. As shown, in each CD phase, only the stations that select the earliest CD slot are filtered. They compete again in the next CD phase. In this way, as the CD phase proceeds, the number of contending stations decreases and the collision resolution probability (i.e., the probability that only one station selects the earliest CD slot in each CD phase) increases. Note that each case has a different channel usage time. In other words, each case is classified according to the channel usage time.

As shown in Figs. 1(c) and (d), transmission fails when all stations select the same CD slot or some stations select the earliest CD slot. In each case, the wasted channel time is different. By an appropriate arrangement of two such cases in two CD phases, we get three cases of transmission failure based on wasted channel times. Figure 2(d) shows the case when all stations choose the same CD slot in every CD phase. Figure 2(e) shows the case when some stations choose the earliest CD slot at the first CD phase and all the surviving stations choose the same CD slot at the second CD phase. Figure 2(f) shows the case when some stations choose the earliest CD slot at the second CD phase after any failure at the first CD phase. Note that in the latter case more channel time is wasted.

It is worth noting that MP-CSMA/CR has two strong points that contribute to performance improvement. The first one is that only stations that choose the earliest CD slot are filtered in each CD phase and have a chance to retry at the next CD phase. This makes the number of contending stations decrease as the CD phase proceeds, eventually increasing the probability of collision resolution. The second point is that if the collision is resolved at a certain CD phase (i.e.,

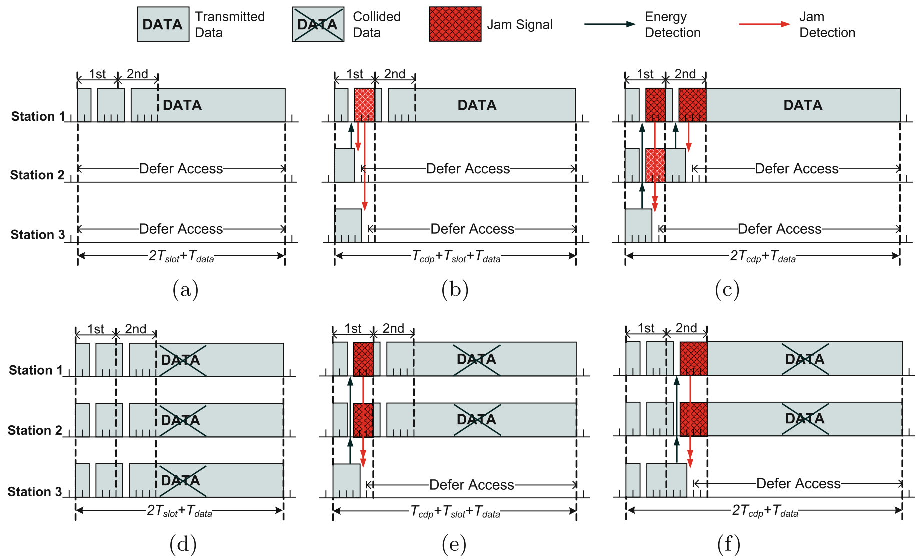

Fig. 2. Event cases in MP-CSMA/CR with two CD phases; (a) 1st success case: only one station accesses the channel, (b) 2nd success case: collision is resolved at the first CD phase, (c) 3rd success case: collision is resolved at the second CD phase, (d) 1st failure case: all stations choose the same CD slot in all CD phases, (e) 2nd failure case: some stations choose the earliest CD slot at the first CD phase and all the surviving stations choose the same CD slot at the second CD phase, (f) 3rd failure case: some stations choose the earliest CD slot at the second CD phase after any failure at the first CD phase.

only one station chooses the earliest CD slot), all the data transmitted during the following CD phases is valid (not corrupted), and just one CD slot in each CD phase is added as the overhead. This does not cause a large transmission overhead although the CD phases remain after a collision is successfully resolved.

4 Results and Discussions

We consider a fully connected wireless network where numerous stations exist [5–7]. This means that the stations are densely located and each station can detect the transmission of any other station in the network (i.e., no hidden or exposed terminal exists). We assume that channel condition is ideal so that channel and sensing errors do not exist. Thus, transmission failure occurs by only access collision [10,11]. In addition, we suppose a saturation condition in which every station has data packets in the buffer all the time and always tries to access the channel [12,13]. We assume a slotted p-persistent access mechanism; thus, every station accesses the idle channel with the probability p $(0 < p \leq 1)$ [6,14]. This access probability p can be adjusted by the network conditions or traffic loads, but we fix it here to focus on the influence of the other parameters on the performance. We also assume that the propagation delay is much smaller than the slot time and is neglected. We suppose that all stations transmit data of the same size and denote the data transmission time by T_{data}, which contains the short inter-frame space and ACK reception time [6]. We denote the length of the CD slot by T_{slot} and set the CD slot length to be the same as the general slot length by considering the worst case scenario because the CD slot time must be shorter than the general slot time to prevent the other stations from trying a new access when a station senses at a CD slot [5]. We denote the number of available CD slots per CD phase by m. For simplicity, we assume that the number of CD slots is fixed in each CD phase. Moreover, we denote the length of one CD period by T_{cdp}, which becomes $T_{cdp} = (1+m)T_{slot}$ because the first slot must include the preamble and the information of the selected CD slot number to preserve synchronization and data integrity at the receiving station [6]. We denote the number of CD phases by h and the number of stations by n.

We compare the proposed MP-CSMA/CR protocol with the original single-phased CSMA/CR protocol.[2] For evaluation, we fix the values of p and T_{slot} and vary the values of n, m, h, and T_{data} within appropriate ranges. We set $p = 1$ (i.e., 1-persistent CSMA) to verify the effectiveness of the proposed scheme under heavy traffic conditions without any access control mechanism. Moreover, T_{slot} is set to 9 µs by considering the OFDM PHY mode specified in the IEEE 802.11 system [15] and the default of the data size T_{data} is set to 512 bytes under the assumption of a data transmission rate of 6 Mbps.

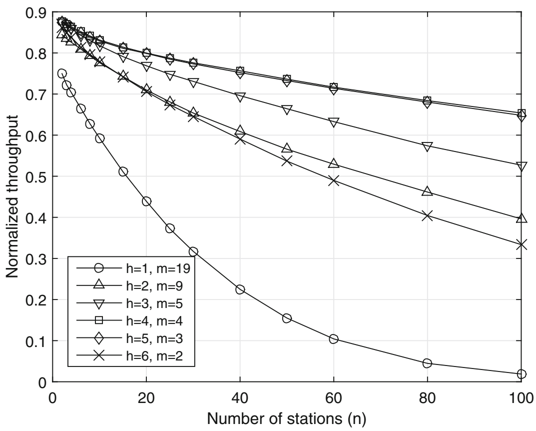

Fig. 3. Throughput vs. number of stations subject to $h(m+1) \leq 20$.

Figure 3 shows the normalized throughput versus the number of stations for some (h, m)-pairs subject to $h(m+1) \leq 20$. The throughput decreases as the

[2] The comparison results of CSMA/CR with the other CSMA-based MAC protocols (i.e., CSMA/CA and WCSMA/CD) can be found in [7].

number of stations increases because of the increase of access collision. Compared to the case of single-phase ($h = 1$), the multi-phase case ($h \geq 2$) significantly improves the throughput even though m is decreased. However, as h increases, the performance gain is gradually reduced and the throughput is maximized at $h = 4$ because a large value of h diminishes the m value and induces more collisions in each CD phase. Hence, it is important for MP-CSMA/CR to determine the (h, m)-pair that will maximize the throughput.

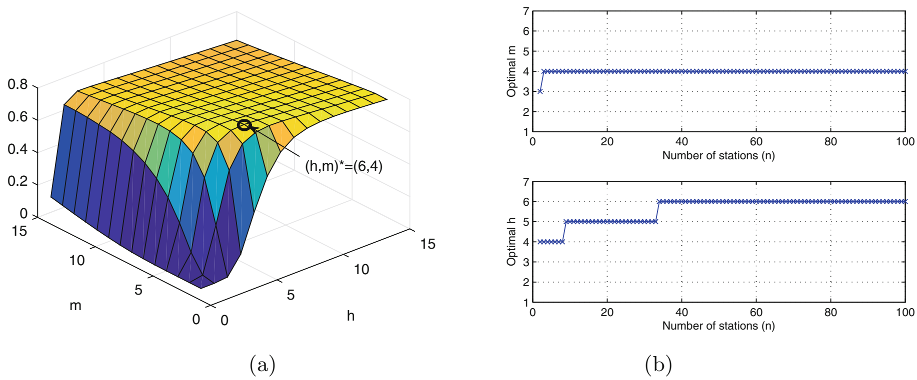

Fig. 4. (a) Throughput vs. (h, m)-pair when $n = 50$ and (b) optimal (h, m)-pair vs. number of stations.

Figure 4(a) shows the throughput versus the (h, m)-pair when n is fixed as 50. As both h and m increase, the throughput increases sharply but begins to decrease gradually at a certain point. That is, the throughput follows a concave form as a function of h and m and it reaches the maximum at $(h, m)^* = (6, 4)$ when $n = 50$. The reason why the decreasing rate of the throughput is smaller than the increasing rate is because once the collision is resolved at a certain CD phase, all the transmitted data except just one CD slot per phase in the following CD phase is valid. Figure 4(b) shows the optimal (h, m)-pair as a function of the number of stations. Here, the optimal (h, m)-pair that maximizes the throughput was found by exhaustive search. Interestingly, the optimal value of m is fixed as 4 except when $n = 2$. On the other hand, the optimal value of h gradually increases from 4 to 6 as n increases from 2 to 100. This observation reveals that h (i.e., the number of CD phases) is more sensitive to the throughput of MP-CSMA/CR than m (i.e., the number of CD slots per phase), in accordance with the change in the number of contending stations.

Figure 5 shows the throughput versus the number of stations when the optimal (h, m)-pair obtained in Fig. 4(b) is applied. For comparison, we fix h and obtain again the optimal m that maximizes the throughput. As shown, the highest throughput is always achieved when the optimal (h, m)-pair is applied based on the change in the number of stations.

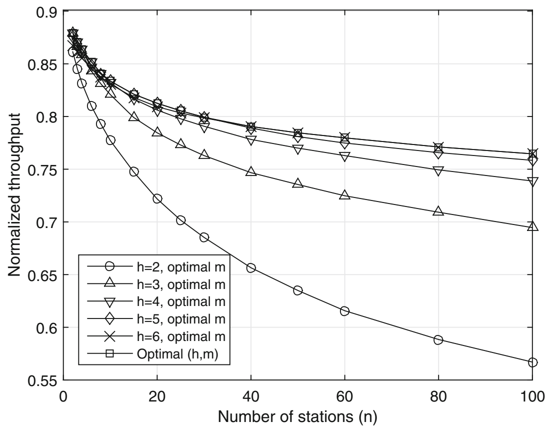

Fig. 5. Throughput vs. number of stations when the optimal (h, m)-pair is applied.

5 Conclusion

In this paper, we proposed the MP-CSMA/CR protocol by extending the typical CSMA/CR protocol to employ multiple CD phases. Results showed that the proposed MP-CSMA/CR significantly improves the throughput compared with the conventional CSMA/CR that uses a single CD phase. Moreover, the results showed that under the conditions of the same length of the total CD period, the increase in the number of CD phases (h) is more effective for achieving successful transmission than the increase in the number of CD slots per phase (m). Regarding the parameters h and m, we revealed that there exists an optimal (h, m)-pair that maximizes the throughput and h is more sensitive to the performance than m. Taking into account its improved performance, we expect that the proposed MP-CSMA/CR can be useful as a distributed MAC protocol in future networks with densely deployed stations. For further study, we will analyze the performance of MP-CSMA/CR numerically.

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