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A novel contention/reservation medium access control scheme for single-hop wireless networks

I-Fen Chao*, Chih-Wei Lai

Department of Electrical Engineering, Yuan-Ze University, Chung-Li 32026, Taiwan

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ABSTRACT

The major challenge pertaining to single-hop wireless networks is to design a medium access control (MAC) scheme to efficiently utilize the scarce wireless bandwidth; whereas the most popular solution, IEEE 802.11 distributed coordination function, achieves only limited performance because of the considerable idle time and the high rate of transmission collisions caused by the backoff procedure at high loads. In this paper, we propose a novel contention/reservation MAC scheme, which aims at ensuring low control overheads and collision-free data transmission to maximize system performance. Our scheme provides an efficient control contention resolution algorithm which resolve one or at least one successful reservation in a time frame, thus only a few numbers of control minislots are necessary for a number of active mobile stations contending for reservations. Moreover, with the help of the broadcast messages from the Access Point, all mobile stations determine a nearly-round-robin and collision-free data transmission schedule in a distributed manner, and also implicitly resolves the well-known hidden terminal problem. Extensive simulation results demonstrate that the proposed MAC scheme achieves exceptional system performance under a wide range of traffic loads and various system parameters, and also shown to be robust even when under attack by malicious mobile stations.

1. Introduction

With the rapid proliferation of wireless communication services, wireless access has emerged as a significant concern for wireless local area networks [1]. During the past two decades, IEEE 802.11 protocols have received the most attention [2,3]. IEEE 802.11 protocols contain two coordination functions, point coordination function (PCF) and distributed coordination function (DCF). PCF provides contention-free services by using a central controller, such as an access point (AP), to poll all mobile stations (MSs) in the AP's access area. If there are lots of inactive MSs in this area, the excessive control overheads consume the bandwidth. Consequently, DCF receives more attention because of its distributed nature. However, as a contention-based protocol, the backoff procedure and data collision problem in DCF limits its throughput, and the system performance exponentially deteriorates as traffic loads increase.

The most challenging problem in DCF, which is based on the carrier sensing multiple access/collision avoidance (CSMA/CA) protocol, is the idle time and the data collision problem caused by the backoff procedure. After the MS senses the channel being idle for a duration of distributed interframe space (DIFS), the MS randomly chooses a backoff timer uniformly between 0 to contention window (*CW*). The MS is allowed to transmit a data packet until waiting a total duration of idle time of the backoff timer (the timer will be frozen when the MS senses a transmission from other MS). In other words, the smaller the *CW* size (the smaller possible backoff timer), the shorter the idle time. Whereas the small *CW* size induces a big probability that more than one MSs choose the same backoff timer and occurring data collisions. Moreover, the *CW* is set to the initial value W_{min} upon a successful delivery, and doubled upon a collision until reaching the maximum value W_{max}, which also incurs short-term unfairness problem [4,5].

Some existing medium access control (MAC) schemes [6–10] improve DCF performance by refining the *CW* size. A fast collision resolution (FCR) algorithm [6] starts with a very small size of *CW*. To reduce the collision probability, the FCR doubles the CW size when a collision occurs or at a deferring state; whereas the FCR reduces the *CW* when successive idle slots are detected. In [7], the GDCF scheme halves the *CW* size when the node has consecutive transmission. GDCF gradually decreases the *CW*, achieving a better contention resolution and thus accommodating a larger number of MSs compared with DCF at the cost of increasing the idle time. Essentially, there are system tradeoffs in setting CW size. The smaller the *CW* size, the less the idle time caused by the backoff procedure, whereas at the cost of increasing the data collision

* Corresponding author.
E-mail address: ifchao@saturn.yzu.edu.tw (I.-F. Chao).

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rate. Some studies have solved this problem by finding the optimal *CW* size [8–10]. All the performance enhancements are still constrained because these schemes are all intrinsically inherited from DCF.

In recent years, DCF-reservation-based MAC schemes [11–13] have been considered. In the EBA mechanism [11], an MS announces its future backoff information within the MAC header of the transmitting data packet to avoid other MSs to select the same back-off timer and thus reduce the data collision rate. The channel reservation MAC (CR-MAC) protocol [12], reserves the next transmission packet by broadcasting the information within the transmitting data packet, which is then virtually queued in all MSs' transmission list. The MSs take their turns to transmit all data packets based on the transmission list. The reservation-based MAC scheme has successfully increased the throughput, but data collision still occurs because each first transmission of a newly arriving MS follows the DCF protocol.

Note that DCF protocols performance drops dramatically when there is a greater number of competing MSs [14,15]. Therefore, the other algorithms design control-contention-resolution methodologies [16–23] to enhance the system performance. These schemes first limit the number of competing MSs that can compete at a single moment in time, and then resolve all or as many control contentions as possible. The work in [16] estimates the number of newly arrival at the beginning of a contention period, while [17] uses a virtual group conception. Instead of using static tree-splitting algorithm, [16] use a dynamic tree-splitting collision resolution algorithm to resolve the contention until reaching a predetermined number of tree splitting. In [18,19], the study adopts a splitting-based collision-resolution algorithm, providing an incremental contention resolution methodology. Moreover, the scheme [21] resolves a maximum number of MSs mostly within a given bounded time. To conclude, these schemes make an attempt to resolve all or a maximum number of the control contentions as quick as possible.

In this paper, we propose a novel MAC scheme that takes advantages of both reservation-based MAC and control-contentions-resolution algorithm for the wireless local area network. The proposed scheme has two prominent features. First, collision-free data transmission is ensured. A transmission frame is divided into contention period of control part and collision-free period of payload transmission. All active MSs, which attempts to send data packets, contend the control minislot reservations. After an MS reserves successfully on any control minislot of the control part, the MS is allowed to transmit data packet(s) in a round-robin order among the other successfully reserved MSs. Second, the control overhead is minimized. Instead of resolving all or as many contentions as possible, our scheme attempts to resolve one or at least one successful reservation. The simulation results also show that the system performs well under only two to five number of control minislots for 10 MSs even under high loads. By eliminating data collisions and reducing control overhead, the proposed MAC scheme achieves exceptional system performance. Moreover, the simulation result demonstrates the proposed MAC scheme is robust even when under attack by malicious MS(s).

The remainder of this paper is organized as follows. In Section 2, we present the network model and the proposed frame structure. In Section 3, we describe the proposed MAC scheme. In Section 4, we present the derivations for approximating the expected length of the required control part, and simulation results are presented in Section 5. Finally, concluding remarks are given in Section 6.

2. Network model and frame structure

The protocols for the infrastructure-based wireless networks are based on frequency-division multiple access (FDMA), time-division multiple access (TDMA), code-division multiple access (CDMA), or combination of these techniques [24–26]. FDMA schemes divide the bandwidth into portions of spectrum, or called as channels. TDMA divides the spectrum into time slots. And, CDMA divides the bandwidth into a collection of codes, so a number of users can use the same channel at the same time. Most protocols in the area use a TDMA scheme. The TDMA protocols are categorized into two duplexing techniques: frequency-division duplex (FDD) provides two carrier frequencies, while time-division duplex (TDD) provides only one carrier frequency. In FDD systems, the uplink frequency transmits traffic from MSs to the AP, whereas the downlink frequency carries traffic (broadcast control information or other broadcast traffic) from the AP to the MSs. TDD systems have only one frequency carrier. FDD allows almost immediate feedback from the AP, whereas TDD schemes can allow asymmetric traffic (from the AP to MSs, or from MSs to the AP), which is appropriate for Web browsing or Internet downloads. In this paper, we focus on the design of a TDMA TDD-based contention/reservation access scheme. However, with some modification, the scheme can also be used with TDMA FDD-based system.

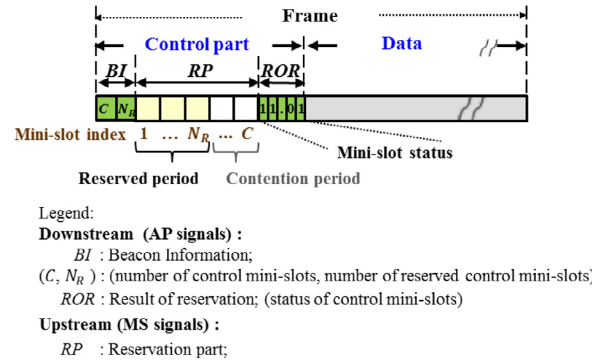


Fig. 1. The frame structure: control part and data.

In this paper, we consider infrastructure-based wireless networks. We assume that a network consists of N MSs and one AP, and that all MSs communicate through the AP. As shown in Fig. 1, based on TDMA systems, time is divided into variable-length time frames, and every frame is subdivided into a contention control part and a contention-free data part. The control part includes beacon information (BI), reservation part (RP), and result of reservation (ROR) fields. The BI, which is issued by the AP, includes two fields: the number of control minislots (C) and the number of reserved control minislots (N_R) for the following RP. The RP consists of C number of control minislots, and is further divided into two periods: reserved and contention periods. The reserved period represents the control minislot indexed from 1 to N_R, each of which belongs to one of the successfully reserved MSs. In addition, the contention period is indexed from $N_R + 1$ to C. During the contention period, all active and non-reserved MSs contend to make a reservation in the control period before transmission. Immediately after the RP, the AP issues the ROR to notify all MSs about the results. The ROR contains C number of bits to specify the status of each control minislot, where “0” denotes unreserved control minislots (idle or collided reservation), and “1” denotes reserved control minislots. The AP directly fills all the control minislots' statuses in the reserved period as “1” (reserved). However, when the AP receives release signal(s) from the remaining MSs, it fills those control minislots' statuses as “0” (not reserved). The advantage of the ROR is that all MSs receive all of the reservation statuses and also receive information on the order of all successful reservations.

In this work, the AP broadcasts BI and ROR to all MSs within the AP's access area. After obtaining the statuses of control minislots based on ROR, each MS executes a distributed algorithm (discussed in the next section), and then decides which MS is allowed to perform a collision-free data transmission. Moreover, a control minislot only consists of MS's identification number, while a data packet consists of a numerous number of data slots. Unlike the studies for the wireless ATM networks [16,26], they try to resolve as many contentions as possible, and followed by the contention period, several MSs are concurrently scheduled to transmit their data via ATM cells within a time frame. In contrast, our control resolution algorithm attempts to resolve one (or at least one) successful reservation within a short period of control part, and immediately followed by a data packet with a relative long duration compared with the control part. Furthermore, when the AP attempts to broadcast information/traffic to MSs, the AP is operated as a MS (contend for reservation, and then transmit data) if a TDMA TDD-based system is adopted. However, if the system is designed by a TDMA FDD-based system, the AP directly uses a downlink frequency channel to broadcast traffic to MSs.

3. Proposed medium access control scheme

In this section, we present a novel contention/reservation MAC scheme. We first describe the control part reservation, and then introduce the transmission scheduling algorithm and fairness methodology design. Finally, we present simple examples to describe the MAC operations in detail.

3.1. Control part reservation

The proposed MAC scheme is detailed in the flow chart as shown in Fig. 2. At the beginning of the control part, the AP broadcasts the BI to all MSs. The BI enables the dynamic setting of the number of control minislots (C) and also facilitates synchronization among MSs. An active and non-reserved MS (the reserved status, *Rev*, is initialized to be false), which attempts to transmit data, first waits and reads the BI and then distinguishes the range of the reserved and contention periods of RP. The non-reserved MS (i.e., $Rev =$ false) then randomly selects one control minislot in the contention period of RP (in the range from $1+ N_R$ to C) for reservation. If more than one MS selects the same control minislot, a control collision occurs; otherwise, the MS reserves successfully. If at least one MS reserves a control minislot successfully, one of the MSs is allowed to transmit a data packet (described later). However, if no MS reserves successfully, the AP issues another BI to initiate another control part. After the AP receives all the control signals in the RP, the AP broadcasts the reservation result, ROR, to the MSs. All the MSs receive information about the reservation statuses and also obtain the sequence orders of all the successful reservations.

It is important to note that the AP is allowed to dynamically modify the C field in BI according to the traffic loads. If too many control collisions occur, the number of control minislots C must increase to reduce the control collision probability, whereas if there are several idle control minislots (can be configured as one of the system parameters), the number of C must reduce to increase bandwidth utilization. Unlike most previous control slot resolution algorithms, which resolve all or as many contentions as possible, our scheme attempts to resolve one or at least one successful reservation. Therefore, as shown in the simulation results, under the system parameter ($C = 2$), the network system averagely requires only two to five number of control minislots for a small group of MSs (e.g., $N = 10$). Compared with DCF, where the *CW* size is specifically set between 32 and 1024 time slots, the control overhead of our proposed scheme is substantially reduced. Furthermore, the ROR of the proposed MAC further implicitly resolves the hidden terminal problem without using request to send (RTS) / clear to send (CTS) handshaking as it does in IEEE 802.11 DCF, thus contributing to control overhead reduction.

3.2. Transmission scheduling and fairness design

The transmission scheduling is basically based on the result of reservation (ROR) and each MS determines the same transmission scheduling in a distributed way. If a non-reserved MS (i.e., $Rev =$ false) randomly selects a control minislot and successfully reserves in the RP, then the index of the selected control minislot is referred as its *reservation-index*. While if the MS reserves unsuccessfully, then the MS waits the next BI to make another reservation. The transmission scheduling is simply defined as follows: when a reserved MS's *reservation-index* is the minimum index among all the reserved control minislots, then the MS is allowed to transmit a data packet at this time frame.

To reduce the probability of control collision, the MS that has made a successful reservation will retain a control minislot (keep a value of *reservation-index*) in the following control parts until the MS has no packet in queue or reaches a maximum predetermined number of transmissions. At that time, the reserved MS ($Rev =$ true) sends a release-signal at its *reservation-index* of RP to release its control minislot, and also set *Rev* to false for being a non-reserved MS again.

Note that the values of “1” and “0” are scattered in ROR because of the release-signal(s) and random contention reservations. All successful reservations are re-arranged (put together in the reserved period of RP) and rotated to facilitate the fairness. Therefore, each MS needs to compute its *next reservation-index* of RP for the following frame. To achieve fairness, in the next control part, the first successful reservation (which has already sent a data packet) is shifted to the last control minislot in the reserved period, and the second successful reservation becomes the first control minislot in the reserved period; the others are rotated accordingly.

To conclude, once a MS wishes to send a data packet, and then it waits for the following BI. After obtaining the range of the contention period based on BI, the MS randomly selects one control minislot to make a reservation within the contention period. The MS then waits and observes the ROR statuses to know whether having reserved successfully or not. The MS attains a *reservation-index* of RP if it reserves successfully, and is allowed to transmit a data packet at this time frame if it has the minimum index among all the reserved control minislots. Importantly, each MS needs to compute and maintain its *next reservation-index* of RP for the following frame. Based on ROR, each MS then executes the same algorithm to rotate and re-arrange all the successful reservations within the reserved period of RP, and then attains its distinct *reservation-index* of RP, contributing to a collision-free data transmission scheduling.

3.3. Simple examples

The operation of the proposed MAC scheme can be best explained via two simple examples illustrated in Fig. 3(a) and (b), which describes the conditions without/with control part collision, respectively. As shown in Fig. 3, we assume that there are three active MSs (MS I, J, K) and one AP in an infrastructure-based wireless network. We further assume that at the beginning of the network, no active MS is reserved ($N_R = 0$), and the number of control minislots is initialized to be 5. Therefore, the AP broadcasts a BI, which contains the information ($C = 5$, $N_R = 0$). The three active MSs read BI, distinguishing the contention period of RP being within the range of control minislot index 1 to index 5. Therefore, all active MSs randomly choose a number between 1 and 5. Assume MS I, J, K individually select control minislot index 5, 4, and 2 of RP to send the reservation signal. Afterwards, AP receives these signals and knows that no control collision has occurred. Then, AP broadcasts the reservation status “0,1011” via ROR message, to all MSs.

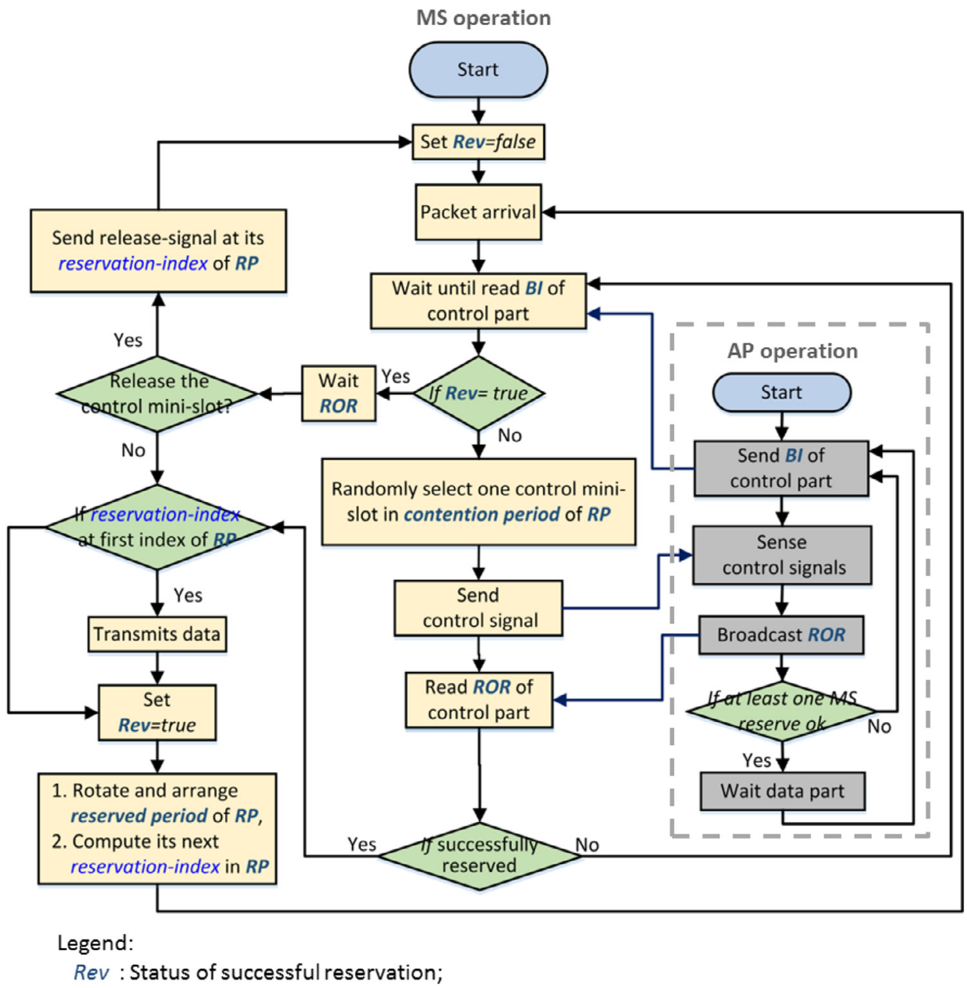


Fig. 2. The flow chart of the transmission procedure between AP and MSs.

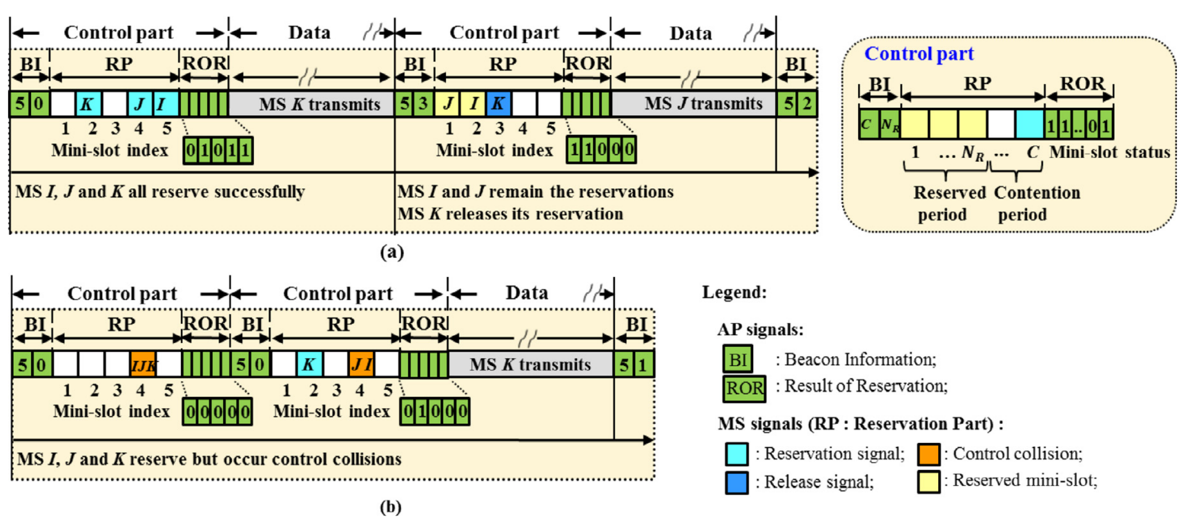


Fig. 3. Expamples of the proposed MAC scheme. (a) Without control part collisions. (b) With control part collisions.

All MSs receive ROR, and find they have successfully reserved. MS *I*, *J* know some other MS(s) are reserved successfully before their *reservation-index* and thus defer their transmissions. And, MS *K* obtains the first chance to transmit data.

In the following, each MS computes its next *reservation-index*. All successful reservations are first re-arranged together into the reserved period of RP, and then rotated to facilitate the fairness. Thus, MS *K*, *J*, *I* are first rearranged at control minislot indexes 1, 2, and 3, respectively. After rotating, the indexes 1, 2, 3 will belong to MS *J*, *I*, and *K*, where the first successful reservation (made by MS *K*) is shifted to the last control minislot in the reserved period. As shown in Fig. 3(a), the reserved period of the next control part, where $N_R = 3$ (3 successful reservations), the index is rotated to belong to MS *J*, *I*, and *K*. The MS *J* attains the minimum *reservation-index* (i.e., 1), so it is allowed to transmit a data packet in this time frame.

Note that if the MS still has data to send, it just preserves its own reserved index without sending other control signal, and wait its turn to send data. On the other hand, we assume the MS K has no data to send, so it sends a release-signal to its corresponding reserved minislot (*reservation-index* = 3), resulting in $N_R = 2$ (totally two MSs reserved) for the next control part. AP then broadcasts the reservation status "11,000" via ROR message, and also the next BI of the control part containing the information ($C = 5$, $N_R = 2$).

We next observe the example with control collisions as shown in Fig. 3(b). All MSs concurrently choose a control minislot index 4 to send the reservation signal and make reservation. The AP receives the signals, and finds no one is reserved successfully. Then, the AP broadcasts the reservation status "00000" via ROR message to all MS, which also implies the AP will immediately issue another BI ($C = 5$, $N_R = 0$) to start another control part. Assume MS K randomly selects the second control minislot for reservation, and MS I, J select the 4th control minislot for reservation. Even though MS I, J reserve unsuccessfully, MS K attains the chance to transmit a data packet. Likewise, at the following frame, AP issues another BI ($C = 5$, $N_R = 1$), and MS I, J make another reservations at that time.

To conclude, the reduction of the control overheads and collision-free data transmission substantially maximizes system throughput. Essentially, our MAC minimizes the control overheads, providing collision-free data transmission and also facilitating fairness control. We summarize in the following the major contributions that make our proposed MAC scheme well suited for wireless networks:

- Ensure collision-free data transmission, thus achieving superior system throughput than DCF. The data collision problem of DCF incurs bandwidth wastage, resulting in deteriorating throughput especially at high loads.
- The control overheads of our proposed MAC are generally smaller than the overheads of DCF and PCF. DCF's overhead is proportional to *CW* size because of the backoff procedure. While the polling overhead of PCF is impractically large primarily when there are a large number of inactive MSs, because PCF has to poll all active and inactive MSs within the cell.
- Dynamically adjust the number of control minislots by the AP according to the traffic loads or the customer population within the cell.
- Minimize the control overhead. Instead of resolving all or as many contentions as possible, our scheme attempts to resolve one (at least one) successful reservation.
- Implicitly resolve the well-known hidden terminal problem by broadcasting the ROR message from the AP.

4. Expected length of required control part

In this section, we present a derivation to approximate the expected length of the required control part for transmitting a data packet. The mean length of the required control part depends on the number of control parts required for transmitting a data packet. In our scheme, only one control part is required to transmit a data packet after at least one successful reservation by an MS. Moreover, if no MS is reserved successfully, more than one control part is required.

Assume that the network has a total of N MSs and one AP. In addition, there are N_{active_MS} number of active MSs and N_{pkts} number of data packets in the system. To simplify the derivation, the length of BI and ROR fields in a control part is ignored and C is assumed to be a constant. The computation is derived as follows. First, the probability of the system having α number of data packets arrivals (π_α) is calculated. Second, the probability of the system consisting of n number of active MSs is calculated, given that the system has α number of data packets ($P_{n|\alpha}$). Third, the expected length of the required control part is derived, given that there are n number of active MSs and α number of data packets ($T_{control|n,\alpha}$). Finally, the expected length of the required control part ($T_{control}$) is derived.

We first derive the system occupancy (π_α). Initially, the arrival process is assumed to be a Poisson process with parameter λ. The queueing delay is defined as the time from a new packet arriving at a MS until the packet is allowed to be transmitted. And, the service time is the sum of the time of a control part and the transmission time. Note that the transmission time is the amount of the time from the beginning until the end of a packet transmission, which is the length of a data packet and is assumed to be geometrically distributed with the mean $1/\mu$ slots. For simplicity, we further assume the mean length of a data packet is much larger than the length of a control part. Thus, the system can be approximated to an M/M/1 system. Therefore, the probability that the system has αnumber of data packets (π_α) is denoted as follows:

$$\pi_\alpha = Pr[N_{pkts} = \alpha] = \rho \cdot (1-\rho)^\alpha. \tag{1}$$

where $\rho = \lambda/\mu$.

Subsequently, we would like to compute the number of active MSs exists in the system when there are αnumber of data packets. Thus, we derive the probability that the system has n number of active MSs given that the system hasαnumber of data packets ($P_{n|\alpha}$):

$$P_{n|\alpha} = \Pr[N_{active\_MS} = n | N_{pkts} = \alpha] = \psi_{n|\alpha} \Big/ \sum_{j=1}^{\omega} \psi_{j|\alpha}. \tag{2}$$

where $\omega = \min(\alpha, N)$, $n < \alpha$ and $n \le N$; if $\alpha < N$, then $n = 1, 2, 3, \ldots, \alpha$, whereas if $\alpha \ge N$, then $n = 1, 2, 3, \ldots, N$. In addition, $\psi_{j|\alpha}$is the total number of cases where the packets are generated from j number of active MSs under the condition that αdata packets are presented in the system (where $\alpha \ge j$). In other words, $P_{n|\alpha}$ is computed as the ratio of the total number of cases where αdata packets are generated from n MSs to the total number of cases that αdata packets are generated in the system.

To compute $\psi_{j|\alpha}$, we separate the derivation into two cases. The first case is $j < N$, and α could be any value ($\alpha < N$or$\alpha \ge N$). Choose j number of MSs from N MS. Each of the j MSs generates one packet; thus, $\alpha - j$ number of packets are generated from the chosen j MSs, yielding

$$\psi_{j|\alpha} = \binom{N}{j} \cdot j^{\alpha-j}, \text{ if } j < N. \tag{3}$$

In the other case ($j = N$ and $\alpha \ge N$) (where the condition $\alpha < N$ does not hold), all of the N MS generate packets. In other words, each MS generates at least one packet, so the derivation is simply by choosing N packets from α packets (thus, each MS currently retains a packet). And, then the remaining packets ($= \alpha - N$) are generated from any of the N MSs as follows:

$$\psi_{j|\alpha} = \binom{\alpha}{N} \cdot N^{\alpha-N}, \text{if} \alpha \ge N \text{ and } j = N. \tag{4}$$

Third, we derive the expected length of the required control part, given that there are n number of active MSs and αnumber of data packets ($T_{control|n,\alpha}$).

$$T_{control|n,\alpha} = E[T_{control} | N_{active\_MS} = n, N_{pkts} = \alpha], n \le \alpha. \tag{5}$$

Before we derive $T_{control|n,\alpha}$, we first compute the probability, $\hat{P}_{rv-ok}(n, c)$, that at least one MS is reserved successfully, given that there are n number of active MSs and c (i.e., $C = c$) number of control minislots in the RP fields. In other words, at least one of the

Table 1
Numerical derivations.

$N_{MS}=n$	$N_{pkts}=\alpha$	$T_{control\|n,\alpha}$
$n=1$	$\alpha \geq 1$	$T_{control\|1,\alpha} = \frac{2}{\hat{P}_{rv-ok}(1,2)}$
$n=2$	$\alpha \geq 2$	$T_{control\|2,\alpha} = \frac{2}{\hat{P}_{rv-ok}(2,2)} \cdot \frac{1}{\alpha} + 2 \cdot \frac{\alpha-1}{\alpha}$
$n=3$	$\alpha = 3$	$T_{control\|3,3} = \frac{1}{3} \cdot \frac{2}{\hat{P}_{rv-ok}(3,2)} + \frac{2}{3} \cdot T_{control\|2,2}$
$n=3$	$\alpha = 4$	$T_{control\|3,4} = \frac{1}{2}(\frac{1}{4} \cdot \frac{2}{\hat{P}_{rv-ok}(3,2)} + \frac{3}{4} \cdot T_{control\|2,3})+$ $\frac{1}{2}(\frac{1}{4} \cdot \frac{2}{\hat{P}_{rv-ok}(3,2)} + \frac{1}{4} \cdot 2 + \frac{2}{4} \cdot T_{control\|2,2})$

control minislots has one and only one reservation (without collision). For this derivation, no general equation can be used; thus, we consider $c=2$ as an example:

$$\hat{P}_{rv-ok}(n,2) = \begin{cases} 1, & \text{if } n=1 \\ 0.5, & \text{if } n=2 \\ n/2^{n-1}, & \text{if } 3 \leq n \leq N \end{cases} \quad . \tag{6}$$

According to the geometric distribution, the expected number of tries until a successful reservation is achieved is $1/\hat{P}_{rv-ok}(n,c)$.

We then derive $T_{control|n,\alpha}$. Because there are no simple general equations, we list some of the derivations in Table 1. We only explain some cases of the derivations; other cases can be computed similarly. For $n=1$, with one active MS, the reservation always succeeds irrespective of the number of data packets and thus the control part equals two control minislots (for $c=2$).

For $n=2$, when there are two active MSs, if one is reserved successfully, the other MS must also reserve successfully. Therefore, the first reservation requires $2/\hat{P}_{rv-ok}(2,2)$ control minislots, whereas the remaining $\alpha-1$ packets require the basic two control minislots. Thus, the expected length of $T_{control|2,\alpha}$ is summation of that the required length for the first reservation multiplying with $1/\alpha$ and the other required length multiplying with $(\alpha-1)/\alpha$, as shown in Table 1., where $n=2$ and $N_{pkts}=\alpha$.

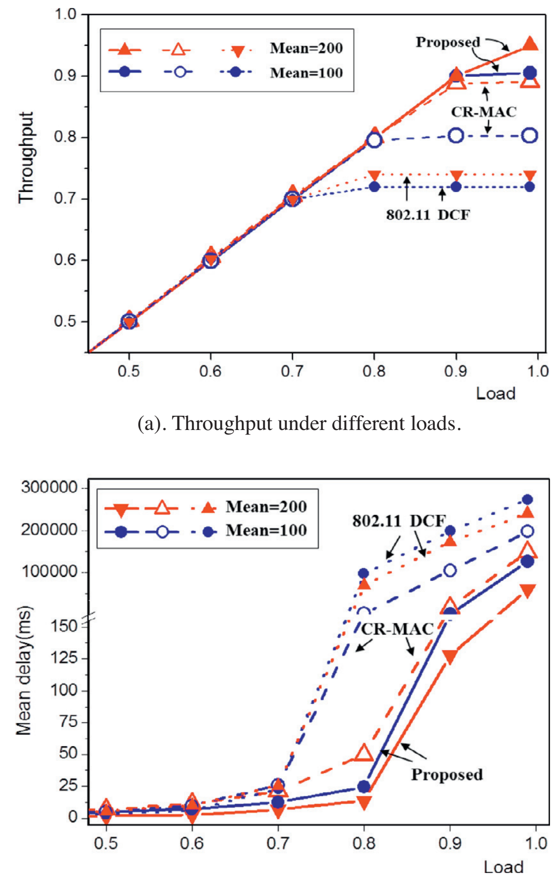
For $n=3$ and $\alpha=3$, the reservation time for the first packet requires $2/\hat{P}_{rv-ok}(3,2)$ control minislots, whereas the other remaining two packets require $T_{control|2,2}$ control minislots. The condition $n=3$ and $\alpha=4$ are derived using two cases: the first MS that reserved successfully has only one data packet, or it has two data packets. Thus, we obtain the mean length of $T_{control|3,4}$ as shown in the Table 1. Consequently, we obtain the mean length of the required control part is as follows:

$$T_{control} = \sum_{\alpha=1}^{N}\left(\pi_\alpha \cdot \sum_{n=1}^{\alpha}(P_{n|\alpha} \cdot T_{control|n,\alpha})\right) + \sum_{\alpha=N+1}^{\infty}\left(\pi_\alpha \cdot \sum_{n=1}^{N}(P_{n|\alpha} \cdot T_{control|n,\alpha})\right). \tag{7}$$

Note that, to simply derive the approximations, we have made two major assumptions. First of all, we assume the mean length of a data packet is much larger than the length of a control part. Thus, the system can be approximated to an M/M/1 system. Second, when the $T_{control|n,\alpha}$ is recursively derived from the other terms of $T_{control|n',\alpha'}$(where $n' < n, \alpha' < \alpha$), we simply assume that there are no newly arrivals before the following control part. As will be demonstrated in the simulation results, the two assumptions lead to the major difference between the simulation and analysis results especially at high loads.

5. Simulation results

In this section, we focus on evaluating the performance of our proposed MAC scheme under unsaturated condition with respect to throughput, access delay, expected length of control part, and robustness under various system settings. The simulation is event-based and written in the C language. It is terminated after reaching a 95% confidence interval. The settings of parameters for simulation are given in the following. Note that although our system can be adapted to a large set of active MSs, we focus the performance on a small set of active MSs. We assume the network has 10 active MSs and one AP. The MSs are numbered from 1 to 10. The number of control minislots is 10 (C=10) without specific indication. The parameters for IEEE 802.11 DCF are: DIFS is 50 μs, the minimum CW size (CW_{min}) is 32 time slots, the maximum CW size (CW_{max}) is 1024 time slots, and one time slot is 20μs. Moreover, a data packet consists of a number of data slots, where one data slot corresponds to one time slot. The length of a data packet is assumed to be geometrically distributed with the mean $\bar{l}$ time slots ($\bar{l}$=100, 200 time slots). The load (L) indicates the number of data slots to be generated per time slot. Therefore, the arrival process of the new data packets (the unsaturated traffic) is assumed to be a Poisson process with parameterλ, where $\lambda = L/\bar{l}$.

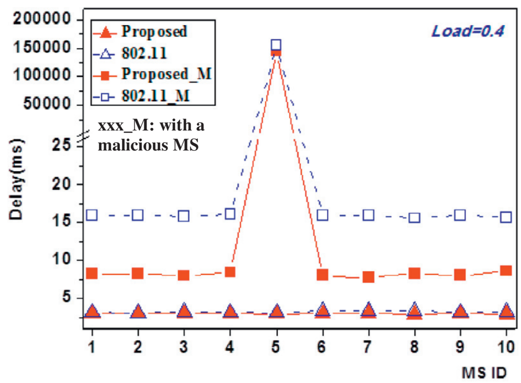


(a). Throughput under different loads.

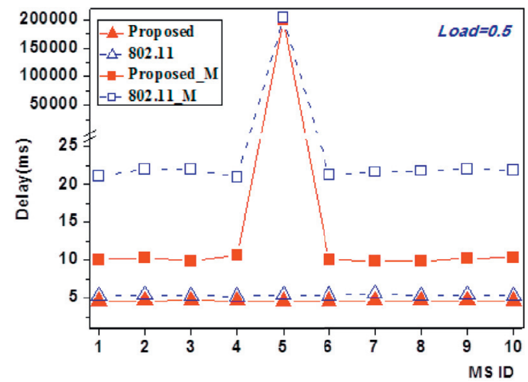
(b). Delay under different loads.

Fig. 4. Throughput and delay comparisons.

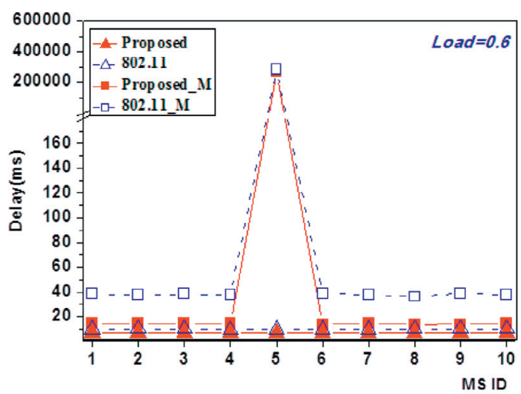
We first draw throughput and delay comparisons among DCF and CR-MAC and our proposed scheme in Fig. 4. The CR-MAC scheme is a DCF-reservation-based protocol [12], which reserves the next transmission packet by broadcasting the information within the modified RTS (Request to Send) control message, and the next packet is then virtually queued in all active MSs' reservation list. The CR-MAC's transmission strategy is then alternately exchanged between DCF-competition mode and reservation mode. As shown in Fig. 4(a), the throughput of DCF is limited to approximately 0.7, and CR-MAC indeed improves the throughput



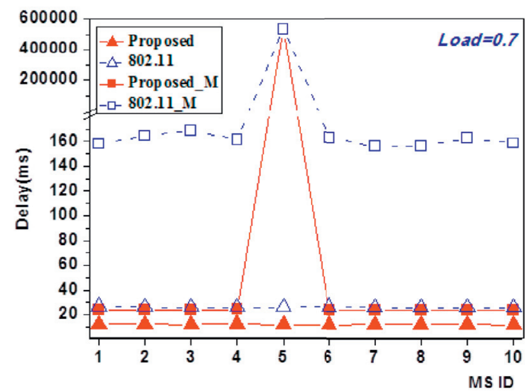
(a). Delay comparisons under medium load (=0.4)



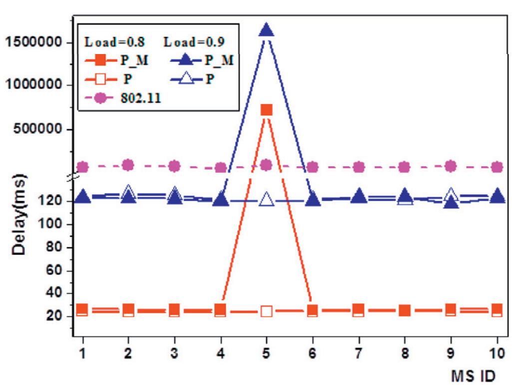
(b). Delay comparisons under medium load (=0.5)



(c). Delay comparisons under high load (=0.6)



(d). Delay comparisons under high load (=07)



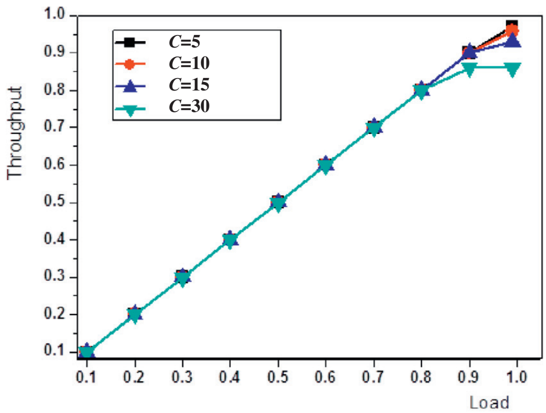
(e). Delay comparisons under very high load (=0.8, 0.9)

Fig. 5. Fairness and robustness comparisons for network with a malicious MS (MS5).

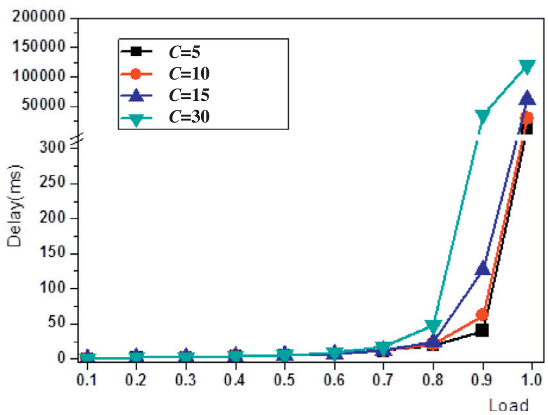
performance, whereas our proposed scheme exhibits extremely high system throughput (e.g., 0.95 for $\bar{l} = 200$). Fig. 4(b) shows that all the schemes have similar mean delay under $L <= 0.6$, but the delay increases with the load for all the schemes. Specifically, DCF undergoes deteriorating throughput and the mean delay at high loads due to data collision and the size of *CW*. And, CR-MAC improves the performance due to collisionless data packet transmission in the reservation period, while still exhibits data collisions in the DCF-competition period. Whereas our proposed scheme outperforms the other two schemes for networks carrying heavy loads due to entirely collision-free data transmission. We further observe the performance effect of the various mean lengths of a data packet. As shown in the results, all the schemes experience delay reduction as the mean length of a data packet increases. This is because a larger data packet size decreases the data collision rate for the DCF. In our scheme, a larger data packet size implies that the control part relatively occupies a smaller proportion of a time frame, resulting in reducing the control overhead wastage percentage.

We next examine in Fig. 5 the impact of a malicious MS. We add a malicious MS (randomly select the MS 5), which attempts to transmit an overly large number of data trying to monopolize bandwidth. The results demonstrate that both schemes are fair with/without a malicious MS, and both schemes are affected by a malicious MS. While with a malicious MS, the DCF scheme performs relatively poorly, raising the the normal MSs' delay from approximately 15 to 160 ms, whereas our scheme increases about 5 to 10 ms, as shown in Fig. 5(a)–(d).

In Fig. 5(e), because DCF only achieves great performance under $L <= 0.7$, thus DCF has extremely high delay even in the absence



(a) Throughput under different length of control part



(b) Delay under different length of control part

Fig. 6. Control part impact.

of malicious nodes case at $L = 0.8$ and $L = 0.9$. However, it is rather surprising to find that our scheme is not affected by a malicious MS at such high loads. Under saturated loads, all MSs have packets to transmit almost at all times. Once the MSs have successfully reserved their own control minislots, they are allowed to transmit their data packets in the round-robin way without affecting by a malicious MS. The results demonstrate that the proposed MAC is more suitable than DCF under high loads.

We now study the impact of the length of the control part in Fig. 6. Note that although the AP is allowed to dynamically modify the C field in BI according to the traffic loads, we here only observe the fixed value of C in each simulation here to fully demonstrate the effect of the length of the control part. We observe the results under various lengths of control part, where $C = 5$, 10, 15 and 30. In the results, as the length of control part decreases, the throughput and delay performance raises. As shown in Fig. 6(a), the network reaches a great throughput performance of 0.97 for $C = 5$; essentially, the exceptional throughput performance is shown to nearly approach the theoretical maximal throughput ($= \bar{l}/(\bar{l} + C)$), which is derived from excluding the overhead of the control part. In Fig 6(b), we observe the delay performance are similar for the two cases, where $C = 5$ and 10. This result demonstrates that the control minislots contentions do not degrade the delay performance for a network with fewer number of control minislots than the number of active MSs, where $C = 5$ and 10 MSs in this simulation. To conclude, under unsaturated condition, a small size of a control part has already led to great system performance. However, under saturated condition, the size of a control part must be increased with the number of active MSs, which are beyond the scope of this paper. Future work should examine how to adjust C

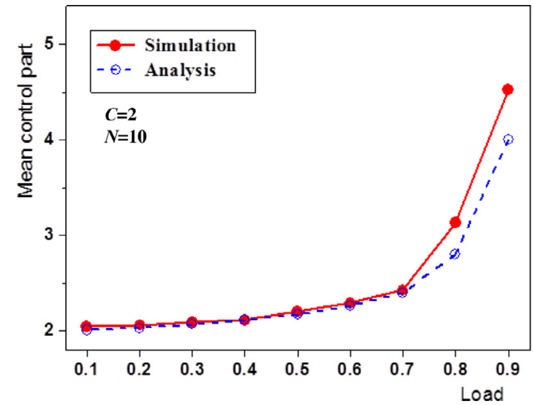


Fig. 7. Analytic and simulation results on mean length of control part.

according to the system statuses, and what is the impact of C under different numbers of MSs under saturated condition.

Finally, we compare the expected length of the required control part in the analytic and simulation results, as shown in Fig. 7. We observe the results under fixed-length control part, where $C = 2$. The analytic results, derived from Section IV, are nearly in agreement with simulation results for medium and low loads, whereas at high loads, the approximation results incur small tolerance. In addition, the results indicate that the length of the required control part increases with loads, but averagely require less than 5 control minislots for 10 MSs. To conclude, the system only requires very small control overheads, thus maximizing the system throughput.

6. Conclusions

We have proposed a novel contention/reservation MAC scheme for single-hop wireless networks. The scheme demonstrates two prominent features. First, it provides an efficient control-contention-resolution mechanism that resolves one (or at least one) successful reservation, resulting in only few numbers of control minislots are needed for a number of active mobile stations contending for reservations. As revealed in the simulation results, under the system parameter ($C = 2$), the network system averagely requires less than five number of control minislots for a small group of MSs (e.g., $N = 10$). Second, collision-free data transmission is ensured. Once an MS reserves successfully on any control minislot, the MS is allowed to transmit several data packets in a round-robin order among the other successfully reserved MSs. With the help of the broadcast messages from the AP, all mobile stations determine a collision-free data transmission schedule in a distributed manner and also implicitly resolve the well-known hidden terminal problem. To conclude, by reducing the control overheads and fully eliminating the data collisions, the scheme exhibits exceptionally high system performance compared with the conventional IEEE 802.11 DCF and PCF protocols.

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I-Fen Chao received M.S. and Ph.D. degrees in Computer Science and Information Engineering from National Chiao Tung University, Hsinchu, Taiwan, in 1994 and 2010, respectively. From 1995 to 1998 she was at CCL/ITRI, working on personal communications systems. From 1998 to 2003 she was with Faraday Technology Corporation, Hsinchu Science Park, Taiwan, as a technical manager working on an embedded OS/system. She is currently an Assistant Professor in the Department of Electrical Engineering at Yuan Ze University, Taiwan. Her current research interests include high-speed networks, optical networks, and wireless access networks.

Chih-Wei Lai received an M.S. degree in the Department of Electrical Engineering from Yuan Ze University, Taiwan, in 2015. He is currently a software engineer. His research interests include high-speed networking and wireless access networks.