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Distributed multichannel MAC protocol for IEEE 802.11 ad hoc wireless LANs☆

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Abstract

The IEEE 802.11 standard supports several independent and equal-capacity communication channels, which can be shared simultaneously and accessed by mobile stations in existing wireless local area networks (WLANs). However, under the restriction of one transceiver per network adapter, these mobile stations can only access one of these communication channels and, thus, the remainder channels are wasted inevitably. A multichannel carrier sense multiple access (CSMA) protocol, multichannel multiple access (MMA) protocol, is proposed in the paper for supporting parallel transmissions under the above single transceiver constraint. The MMA protocol enables mobile stations to contend for access of multiple data-transferring channels through the use of a dedicated service channel during each *contention reservation interval* (CRI). After granting the access right of these channels, these mobile stations can transmit data frames over different channels by using a pre-defined channel scheduling algorithm (CSA) in a distributed manner. The time complexity of the proposed heuristic CSA is $O(|X|\log|X|+|X|\times M^2)$ where $|X|$ and M denote the number of successful requests in the CRI and the number of available channels, respectively. An improved MMA$^+$ protocol with extending reserved transmission opportunities is also introduced and the goal is to maximize the channel utilization further. Simulation results show that the proposed MMA with CSA achieves a much higher throughput than conventional IEEE 802.11 WLAN with single channel. Simulation results also indicate that the achievable peek network throughput is not linearly proportional with the number of channels because of the native collision problem caused by single transceiver.

Keywords: Ad hoc; Algorithm; LAN; MAC; Protocol; Scheduling; Wireless

1. Introduction

The wireless communication technology has been applied to modern consumer products in the recent years. Practical applications of the wireless technology include, for instance, (1) communication establishment between members of a rescue team in a rural area without pre-established communication infrastructure; (2) exchanging of on-line information between presenter and audience at a conference in real time; and (3) playing instant messages or online games between high school classmates. This enables wireless communication to play a major role in our normal life and society.

The goal of the next-generation wireless communications is envisaged to support high-data-rate, high-capacity, and broadband communication capabilities. With a selected modulation scheme, high-capacity wireless communications may be realized by using either a single wide-band channel or multiple narrow-band channels partially overlapping to each other. The latter approach, which we consider in this paper, has been adopted by the IEEE 802.11 wireless local area networks (WLANs) standard [6]. The radio spectrum of IEEE 802.11 standard is designated to the unlicensed ISM (Industrial, Science, and Medical) bands, which is at the 2.4 GHz (2.4–2.4835 GHz) band and is available for use throughout most of the world [13]. In the direct sequence spread

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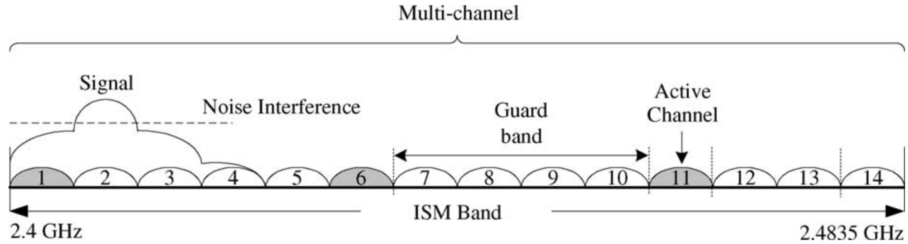


Fig. 1. An illustration of the implement of ISM band that is divided into several channels.

spectrum (DSSS) specification, the 83.5 MHz radio spectrum, shown in Fig. 1, is divided into 14 channels and some of them can be used simultaneously. At least 25 MHz or 30 MHz guard band should be considered to avoid electromagnetic wave interference that can degrade the transmission quality if more than one mobile station transmits data frames at the same location meantime.

As a result, three available channels can be utilized concurrently for data transfer in IEEE 802.11 WLANs. For instance, if the channel data rate is 2 Mb/s (or 11 Mb/s in IEEE 802.11b), the aggregated network bandwidth in WLANs will be 6 Mb/s (33 Mb/s). Unfortunately, due to the single transceiver constrain, the current standard specifies only the definition for medium access control (MAC) operations on single channel mode. Intuitively, the simplest way to achieve multichannel access is to upgrade mobile stations to equip several transceivers [7,24–26]. But from the cost-effectiveness point of view, it is worth to enhance IEEE 802.11-based MAC protocol to support multichannel access with a single transceiver.

The performance of multichannel slotted ALOHA system, where multiple equal-capacity channels are shared by many users, has been analyzed in [2,15,27,28]. The design of efficient wireless MAC protocols and the evaluation of their performance in the presence of multichannel transmission (especially in the IEEE 802.11 WLANs) are still an open issue [1,11,22,25,26]; and the common idea as proposed in these papers is somewhat similar to the frequency-division multiple access (FDMA) scheme used in cellular phone systems. However, in ad hoc networks, there is no centralized controller and the channel assignment must be done in a distributed manner via carrier sensing (such as using the carrier sense multiple access, CSMA scheme) [12,17,18,21]. Thus, those proposed schemes as mentioned above would not be suitable for ad hoc networks.

In this paper, we disclose a new multichannel CSMA protocol for supporting multichannel transmission by using a single transceiver in the ad hoc WLANs. Moreover, this new protocol is compatible with the IEEE 802.11 standard where all mobile stations can hear each other as defined in the standard [6]. In papers [7,24–26], solutions have also been proposed to adopt dual transceivers in order to achieve the similar goal. For instance, Wu et al. [26] proposed a so-called dynamic channel allocation (DCA) scheme, which uses one transceiver fixing to a dedicated control channel for contention and another tunable transceiver for accessing the remainder channels for data transmission. When a station receives a request-to-send (RTS) control frame in the control channel, it will scan all data channels and choose the first idle channel to inform the sender for transmission. Nevertheless, disadvantages for this dual-transceiver scheme include more implementation complexity and higher cost, which make it impractical to be in the present WLAN adapter product. Thus, a contention and reservation-based multichannel multiple access (MMA) protocol is proposed to support multichannel transmissions over ordinary IEEE 802.11 ad hoc WLANs in which each mobile station only equips a single transceiver.

The remainder of this paper is organized as follows: in Section 2, we describe the proposed MMA protocol in detail. In Section 3, we propose a channel scheduling algorithm (CSA) for the MMA protocol to support multichannel scheduling and data allocation. In addition, an enhanced MMA$^+$ protocol is also presented with improved channel utilization. In Section 4, mathematical models with their analysis and performance comparisons of the proposed MMA and MMA$^+$ protocols are disclosed. Simulation models and results are shown in Section 5. The conclusions and possible future works are given in Section 6.

2. Multichannel multiple access (MMA) scheme

2.1. The MMA protocol

The main reason for using multiple channels is to utilize the potential raw bandwidth available on all channels. However, there are several challenges needed to be solved before obtaining the possible network throughput gain. These problems are presented as follows:

- *P1*. How to allow mobile stations to contend for channel access right in a single transceiver environment?
- *P2*. How to ensure every mobile station can perform the pre-defined channel scheduling algorithm distributedly and correctly once the channel contention is resolved?
- *P3*. How to allocate successful requests (source–destination pairs) using proper channels in a collision-free manner such that the channel efficiency is

maximized? This problem is especially difficult in a distributed system.
- *P4*. How to do broadcast and/or multicast in a multichannel system?

In general, the collision probability of a requesting attempt can be minimized accordingly if all mobile stations are equally allocated to all channels. However, because of the one transceiver constrain, transmissions are usually performed on the same channel by using a request-to-send and clear-to-send (RTS/CTS) handshaking scheme to conquer the *hidden terminal* problem [3,4,10,23]. To solve the first problem (P1) mentioned in the previous paragraph, in the proposed MMA protocol: we (a) divide the radio spectrum into M available channels as described in the specifications of the IEEE 802.11 standard; then, (b) allocate a dedicated *contention* channel to allow mobile stations to contend for the channel resource; and (c) use the remainder channels as *data* channels permanently. To further enhance the channel utilization, the dedicated contention channel can also be used to transmit data frames after the contention period is over. Fig. 2 illustrates the channel usage of the MMA protocol in which channels C_1–C_{M-1} are data channels and channel C_0 plays the role of the contention channel and data channel, alternatively. The acronyms DIFS and SIFS represent the distributed inter-frame space duration and short inter-frame space duration, respectively.

The second and third problems (P2 and P3) can be resolved by adopting an appropriate channel scheduling algorithm (CSA) to distribute successful requests over the available channels properly. However, especially in a distributed system, there is an additional problem, which needs to be solved. That is how to announce successful requests to all mobile stations correctly so each channel access arrangement will not interfere with other ongoing transmissions on data channels. In order to overcome this problem, we partition channel access period, shown in Fig. 2, into two alternative and non-overlapping time intervals: the *contention-reservation* interval (CRI) and the *contention-free* interval (CFI). In the MMA protocol, the CRI is fixed and the interval of CFI is depending on the contention resolution of a CRI. All mobile stations are enforced to listen to the results of all contentions in CRI since the scheduling information are recorded in RTS and CTS frames. For the sake of compatibility, all contentions in a CRI follow the contention police of IEEE 802.11 Standard. One difference is that data frames are deferred until the beginning of a CFI rather than being sent immediately after a successful RTS/CTS handshaking point. The details of CSA for successful requests will be described in Section 3.

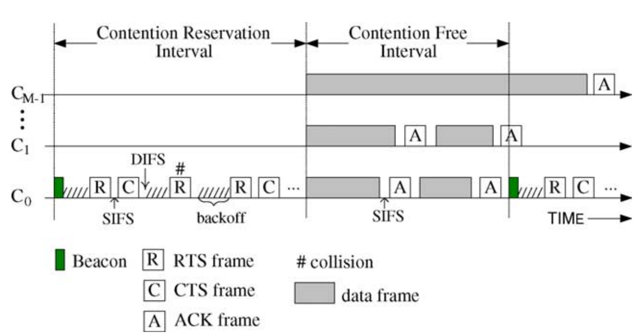


Fig. 2. An illustration of the contention and allocation procedure of proposed MMA protocol.

For the last broadcasting/multicasting problem (P4), there are several approaches can be employed [20]. Since all mobile stations have to stay on channel C_0 during a CRI period in order to collect the contention results, a broadcast/multicast frame can be sent during this period. However, in the enhanced MMA$^+$ protocol, which will be described in Section 3.2, we do not enforce all stations to stay on the contention channel during a CRI period; instead, a broadcast or multicast sender can transmit its frames in several CRIs.

2.2. The beacon operation

In the IEEE 802.11 standard, one member in an ad hoc WLAN is responsible for performing the time synchronization functionality by periodically generating beacon frames In the MMA protocol, beacon frames are also used to announce the starting of a CRI and a CRI time interval. This can be done by appending an additional information element of CRI into the beacon frame. When a mobile station wants to access the medium, it must receive the beacon frame before contending for the medium's access right. If a generated beacon frame does not appear correctly (for example, it is destroyed by noise or the coordinator is moving out of the WLAN), other mobile stations will follow the IEEE 802.11 standard to contend for being the beacon generator. This procedure will continue until a correct beacon frame appears.

3. Channel scheduling algorithm (CSA)

Without loss of generality, a data frame can be any length and a mobile station can send or receive multiple data frames in the CFI period as well The proposed CSA only deals with the unicast data frames since broadcast and multicast frames should be transmitted in the contention channel during CRI.

Given N requests, the problem of finding a proper schedule for these N requests to be served on a multichannel system with a minimized worst-case channel busy period is known to be NP-hard [5]. Recall that successful requests can be detected by every station and data frame transmissions are deferred until the beginning of a CFI. As soon as the CRI is finished, mobile stations will perform the CSA individually to select a channel and determine when to send requests. Let $X=\{x_1,x_2,\ldots,x_n\}$ denotes a set of new arrival requests, where each $x_i=\{s_i,d_i,l_i\}$ represents a request with a transmission period l_i from mobile station s_i to mobile station d_i. Transmission period l_i includes the time period for transmitting data frames, the SIFS interval, and the following ACK control frame. Given a set of traffic requests, the channel/time scheduling problem becomes how to assign a channel and a time interval for each of the requests such that the channel utilization is maximized and the worst-case channel busy time is minimized. Let $A(X)=\{(c_1,t_1),(c_2,t_2),\ldots,(c_n,t_n)\}$ be the *channel/time assignment* of X, where c_i is the assigned channel and t_i is the scheduled starting time for delivering request x_i. In the case of using a single transceiver, a mobile station neither transmit, nor receive data frames in two or more channels at the same time. Thus, we say that a request x_i is *intersected* with another request x_j if ($t_j\le t_i<t_j+l_j$ or $t_j<t_i+l_i\le t_j+l_j$ or $t_i\le t_j<t_j+l_j\le t_j+l_i$) and ($s_i=s_j$ or $s_i=d_j$ or $d_i=s_j$ or $d_i=d_j$). It is desirable for a CSA to be designed efficiently to prevent incurring request intersections.

At first, the CSA sorts the set X by their transmission periods and then assigns them into data channels one by one. Let us assume a WLAN supports M parallel channels; and let $F=\{f_0,f_1,\ldots,f_{M-1}\}$, where f_i stands for the free time of the ith channel. Initially all channels are free; that is, $f_i=0$, for $0\le i\le M-1$. The CSA schedules a request to a data channel each time. Requests with shortest transmission period and channels with the smallest f_i will be considered first. If the channel assignment results in a request intersection, the channel with second earliest free time will be considered. This process is repeated until all conflicts are resolved. Once a channel, say k, is assigned a request, say x_i, we have $c_i=k$ and $t_i=f_k$. Moreover, the new, earliest free time of the kth channel will become f_k+l_i The above scheduling process is repeated until all requests have been scheduled. It is obvious that at most M channels can be available for a request and the worst case for the request is to be assigned to the channel with the latest free time. Since the time complexity for the intersection check is $O(M)$, the time complexity of the CSA will be $O(|X|\log|X|+|X|\times M^2)$ where $|X|$ is the number of successful requests during a CRI. The detailed CSA is shown in Fig. 3.

One way to maximize channel utilization is to assign a request with the shortest transmission period to a channel, which will become free first. If conflict occurs, the second earliest free channel will be considered and so on. The proposed CSA can be treated as request-major algorithm. A channel-major heuristic algorithm can also be used for solving the channel/time scheduling problem. That is, during each assignment, the earliest free channel will be scheduled to find a *proper* request with the shortest transmission period. This means that a number of $|X|$ requests will be checked for each selected channel. It is possible that none of these requests are suitable for a selected channel; therefore, the next earliest free channel will be selected for the next matching attempt until all requests are scheduled. The total time complexity of such a channel-major heuristic algorithm will be $O(|X|\log|X|+(|X|\times M^2)^2)$. Obviously, the request-major heuristic algorithm is better than the above channel-major heuristic algorithm. We also note that both algorithms will not incur internal fragments and some channel capacity might be wasted.

```
Procedure CHANNEL_SCHEDULING
Input: a set X of successful requests and a set F of the channel free time of M channels in WLANs;
Output: a feasible channel/time assignment A(X);
Begin
  Sort request set X by transmission periods;
  For i = 1 to |X|
  Begin
    Unmark all channels;
    For count = 0 to M − 1
    Begin
      Select the unmark channel, say k, that has the earliest free time;
      If no intersection occurs after assigning channel k for request x_i Then
        c_i = k;
        t_i = f_k;
        f_k = f_k + l_i;
        BREAK LOOP
      Else
        Mark channel k;
      End-if
    End-for
  End-for
End
```

Fig. 3. The channel schedule algorithm (CSA).

3.1. Example of MMA protocol

Fig 4 illustrates an example of channel assignment using the proposed MMA protocol. In this example, four independent channels, C_0–C_3, are used. Nine mobile stations, labelled from a through i, are trying to access the medium in the WLAN. Moreover, each mobile station can transmit/ receive data to/from another station directly. Assuming there are six requests sorted as $X=\{(a,b,30),(b,a,35),(c,f,40), (c,i,50),(h,d,50),(e,g,60)\}$. According to the CSA, the first request $(a,b,30)$ with the shortest transmission period will be allocated to C_0 and the free time of channel C_0 will become $f_0=30$. Notice that the transmission period includes the time for transmitting a data frame, an ACK frame, and the necessary SIFS. To schedule the second request $(b,a,35)$ without *intersecting* the first request $(a,b,30)$, the second request must be scheduled on channel C_0 just after the first one; and f_0 is updated to $30+35=65$. The third request $(c,f,40)$ can be successfully allocated to channel C_1 without any conflict. The fourth request $(c,i,50)$ cannot be allocated to channel C_2 because it will *intersect* with $(a,b,30)$ and $(c,f,40)$ simultaneously. Thus, request $(c,i,50)$ will be allocated to channel C_1. Finally, the last two requests $(h,d,50)$ and $(e,g,60)$ are allocated to channels C_2 and C_3, respectively; and we can obtain a feasible channel assignment $A(X)=\{(0,0),(0,30),(1,0),(1,40),(2,0),(3,0)\}$.

From the above exercise, we know that one major drawback of the proposed MMA protocol with CSA is the bandwidth wastage during the CRI and CFI periods. To become an attractive and practical protocol, we introduce a simple enhancement scheme for improving the performance of the MMA protocol in Section 3.2.

3.2. The enhanced MMA (MMA$^+$) protocol

Since each mobile station is equipped with one transceiver, all stations must listen to the contention channel during a CRI period As a result, an amount of $(M-1)\times \mathrm{CRI}_{\mathrm{interval}}$ is inevitably wasted for every CRI. Furthermore, channel capacity is also wasted because of the external fragments caused by the CSA as shown in Fig. 4. One straight forward way to enhance the channel utilization is to overlap the CRI and CFI periods. The concept is that, during a contention interval, data channels can be used to serve data frames that are scheduled in the previous interval (stations got served during a contention interval are on-serving stations). However, it incurs three interesting new problems.

- *P5*. On-serving stations, which cannot listen to the contention channel, will miss the channel status information of the next cycle.
- *P6*. The beacon generator can be one of these on-serving stations; therefore, the next CRI must be started by any of other stations.
- *P7*. The broadcast and multicast frames transmitted in CRI may fail to reach all mobile stations.

To overcome the synchronization problem (P5), the beacon frame needs to contain the channel status information. This can be done by carrying additional information in the beacon frame to tell the exact free times of channels since the last cycle. Based on this information, even though a station has past several contention intervals, it can immediately synchronize with others as soon as it detects a new beacon frame. Problem (P6) can be resolved by treating it as a missing-beacon-frame event as mentioned in Section 2.2. The other mobile stations, who had received the precedent beacon, will follow the standard policy to contend for becoming the new beacon generator. About the last problem (P7), several approaches can be applied. For example, one may enforce a broadcast or multicast sender to transmit a broadcast/multicast data frame multiple times spreading across different CRIs. An alternative approach is to enforce all mobile stations periodically stay on

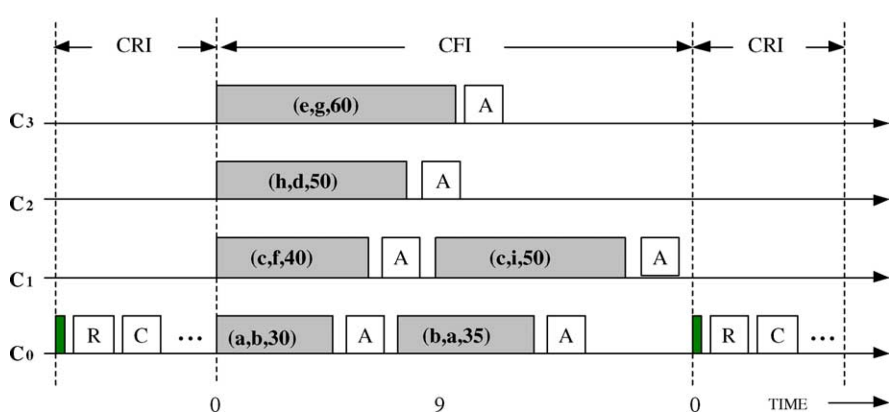


Fig. 4. An example of channel assignment by CSA for four channels.

Procedure ENHANCED_CHANNEL_SCHEDULING
Input: a set X of new arrival requests and a set F of the channel free time of M channels in WLANs;
Output: a feasible channel/time assignment $A(X)$;
Begin
  Call CHANNEL_SCHEDULING;
  If the earliest free channel is not the contention channel **Then**
    Swap the scheduled requests in the earliest free channel and in the contention channel;
  End-if
End

Fig. 5. The enhanced channel scheduling algorithm (ECSA).

the contention channel as the original MMA protocol does; thus, broadcast/multicast data frames can be delivered during these periods. The difference is that the original MMA protocol needs to meet this constrain in every CRI and the enhanced MMA$^+$ protocol does not.

There is another challenge needed to be conquered: how to further minimize the wasted channel bandwidth during the CFI? If longer fragments among channels can be scheduled in data channels, the next CRI can be started at the earliest time and the bandwidth wastage can be minimized. This goal can be easily achieved by swapping the shortest scheduled request in channels with the scheduled request in the contention channel. The enhanced CSA (ECSA) is listed in Fig. 5.

3.3. Example of MMA$^+$ protocol

Consider the example shown in Fig. 4 again. In order to illustrate the consecutive schedules in the MMA$^+$ protocol, we assume new requests in the next CRI are $X'=\{f,d,30\}$, $(f,j,35)$, $(k,l,40)$, $(h,o,60)$, $(m,n,80)\}$. Recall the earliest free channel of the channel/time assignment $A(X)$ is channel C_2 (as shown in Fig. 6(a)). From the descriptions mentioned in Section 3.2, scheduled requests in channels C_2 and C_0 are swapped by the ECSA and the next CRI is started at time 50 as shown in Fig. 6(b). For new request set X', the following channel/time assignment $A(X')$ will become $A(X')=\{(0,50+\text{CRI}), (0,80+\text{CRI}), (2,50+\text{CRI}), (3,50+\text{CRI}), (1,90)\}$. Similarly, the earliest free channel is channel C_2 (with channel free time 90+CRI as shown in Fig. 6(c)) and requests on it will be migrated to the contention channel. The swapped channel/time assignment is shown in Fig. 6(d).

4. Comparative throughput analysis

4.1. The model

Before analyzing the network throughput, we first introduce the following notations We let L_{type} denote the length of a 'type' frame (for example, L_{RTS} is referred to the length of a RTS frame) and $\text{RTS}=\text{PHY}_{\text{hdr}}+L_{\text{RTS}}$ be the precise frame length in the PHY layer. The length m of a transmitted data frame is equal to $\text{PHY}_{\text{hdr}}+\text{MAC}_{\text{hdr}}+L_{\text{data}}$ and is measured in normalized time units (slots). Notation τ denotes the propagation delay plus the carrier sensing delay.

Let T_c and T_s denote the expected time interval wasted by collision and the needed time interval spent for one successful handshaking, respectively. Here, we use the superscript 2 to denote the two-way RTS/CTS handshaking. A simple observation reveals that

$$\begin{cases} T_c^2 = \text{RTS} + \tau \\ T_s^2 = \text{RTS} + \tau + \text{SIFS} + \text{CTS} + \tau \end{cases} \tag{1}$$

For simplicity, the following assumptions are made:

- The effect of frame errors due to bit errors introduced by channel noise is ignored.
- The station's mobility is limited.
- There is no hidden terminal and there are N stations in the 'fully-connected' network.
- There are M available channels.
- All stations can detect collisions perfectly.

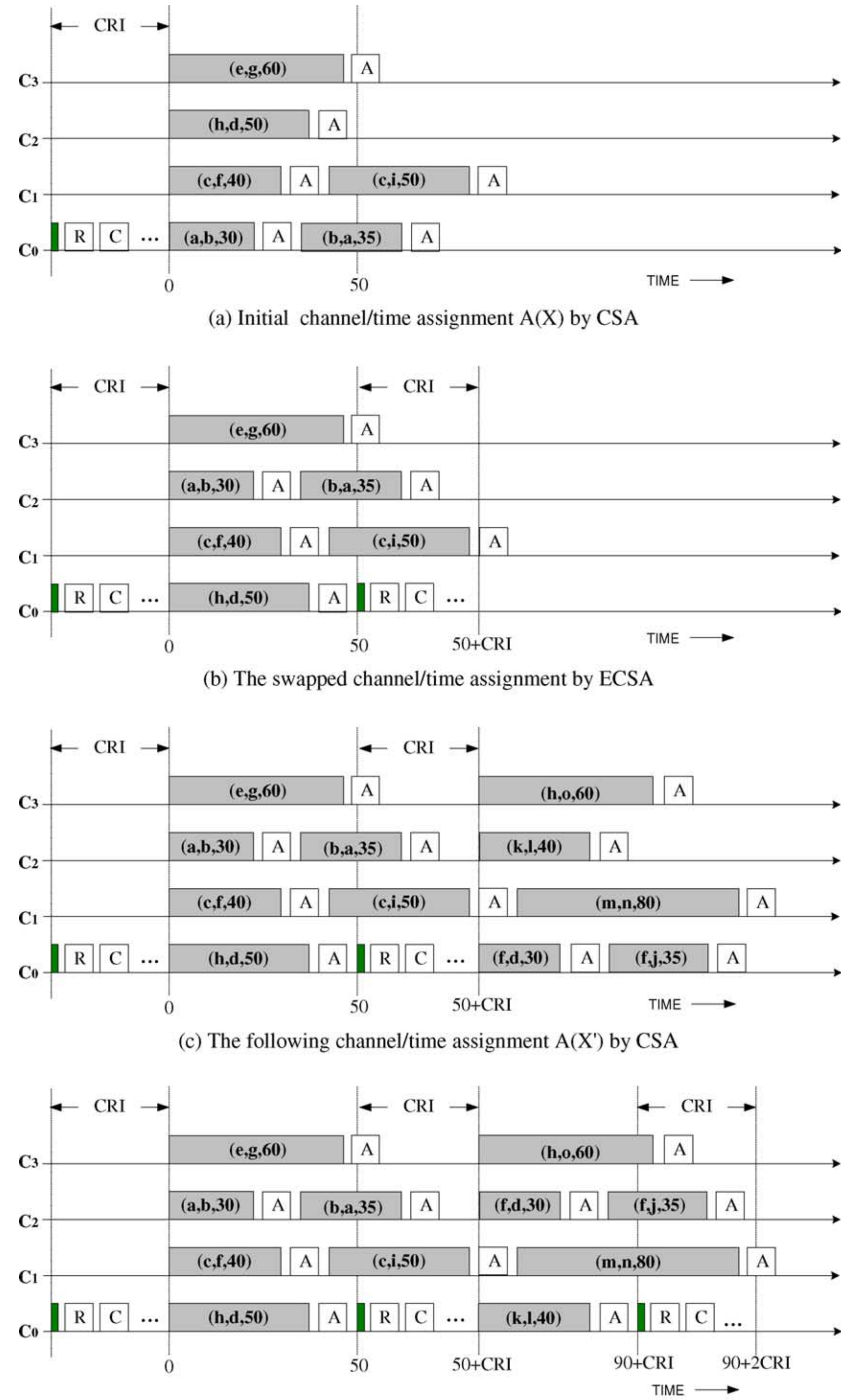
We will also assume that the message arrival time at a queue in each station is a Poisson process [8,14,16]. Under this assumption, Poisson statistics state that the probability $P_n(t)$ of exactly n packets arriving in a time interval t per each station is given by

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \tag{2}$$

where λ represents the mean packet arrival rate of a station and $n=0,1,2,\ldots,\infty$.

For simplicity, we let $P_{\text{idle}}(t)$ denote the probability of a station to successfully sense a channel *idle* in time interval t. In other words, the $P_{\text{idle}}(t)$ can be treated as the probability that a station detects no other stations are transmitting data in the network during the observing time interval t and can be derived by

$$P_{\text{idle}}(t) = e^{-\Lambda t} \tag{3}$$



(a) Initial channel/time assignment A(X) by CSA

(b) The swapped channel/time assignment by ECSA

(c) The following channel/time assignment A(X') by CSA

(d) The swapped channel/time assignment A(X') by ECSA

Fig. 6. An example of channel assignment by enhanced CSA (ECSA) for four channels.

where $\Lambda = N\lambda$ is the total packet arrival rate in the network.

By considering the propagation delay, the channel capacity may be wasted by two colliding RTS control frames that are partially overlapping each other. Such extra channel wastage $\bar{\Upsilon}$ can be derived by the following equation [23]

$$\bar{\Upsilon} = \tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda}. \quad (4)$$

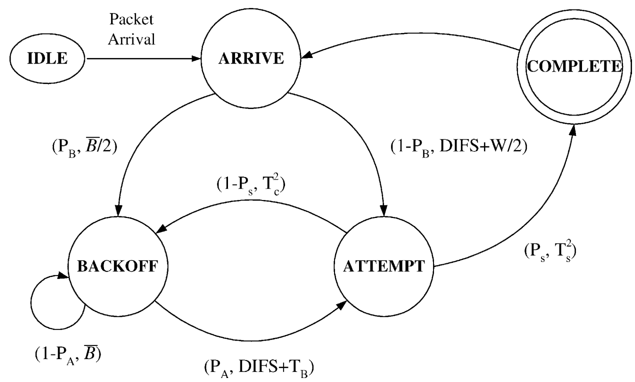


Fig. 7. The state transition diagram of contention with handshake reservation in CRI.

Therefore, the average channel busy period $\bar{B}$ in a CRI is given by

$$\begin{aligned}\bar{B} &= \bar{\Gamma} + T_c^2(1 - P_{\text{idle}}(t)) + T_s^2 P_{\text{idle}}(t)\\ &= \bar{\Gamma} + T_c^2(1 - e^{-\Lambda\tau}) + T_s^2 e^{-\Lambda\tau}\\ &= \text{RTS} + (\text{SIFS} + \text{CTS} + \tau)e^{-\Lambda\tau} + 2\tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda},\end{aligned} \quad (5)$$

and the expected duration of idle period between two consecutive busy periods is $1/\Lambda$.

We also assume that there are four states in our transmission model: ARRIVE, BACKOFF, ATTEMPT, and COMPLETE. The transitions between and corresponding probabilities of these four states are shown in Fig. 7. The ARRIVE state is visited when a packet first arrives at a station. Once a station has a packet to transmit, it will first sense the channel idle for a DIFS duration and then choose a random backoff time for counting down. If it senses channel busy in the DIFS interval, it will transit its state from ARRIVE state to BACKOFF state. The corresponding probability P_B can be expressed as

$$\begin{aligned}P_B &= \bar{B} \times \left[\frac{1}{\Lambda} + \bar{B} + \text{DIFS} + W/2\right]^{-1}\\ &= \left[\text{RTS} + (\text{SIFS} + \text{CTS} + \tau)e^{-\Lambda\tau} + 2\tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda}\right]\\ &\quad \times \left[\frac{1}{\Lambda} + \text{RTS} + (\text{SIFS} + \text{CTS} + \tau)e^{-\Lambda\tau}\right.\\ &\quad \left. + 2\tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda} + \text{DIFS} + W/2\right]^{-1},\end{aligned} \quad (6)$$

where $W/2$ is the mean value of the first backoff countdown. In this paper, we assume the minimum backoff window size $W = 32\delta$ and the maximum window size is 1024δ (as described in the IEEE 802.11 specifications), where δ is the notation of a slot (20 μs). According to the binary exponential backoff algorithm in CSMA/CA protocol, the backoff delay $b(n)$ of the nth retransmission ($0 \le n \le 5$) can be calculated by the following recursive functions:

$$\begin{aligned}b(0) &= W,\\ T_B &= P_s(\tau)\frac{2^0 W}{2} + (1 - P_s(\tau))b(1),\\ b(1) &= P_s(\tau)\frac{2^1 W}{2} + (1 - P_s(\tau))b(2),\\ b(2) &= P_s(\tau)\frac{2^2 W}{2} + (1 - P_s(\tau))b(3),\\ b(3) &= P_s(\tau)\frac{2^3 W}{2} + (1 - P_s(\tau))b(4),\\ b(4) &= P_s(\tau)\frac{2^4 W}{2} + (1 - P_s(\tau))b(5),\\ b(5) &= \frac{2^5 W}{2} = 2^4 W.\end{aligned} \quad (7)$$

Then, solving Eq. (7) for T_B leads to

$$T_B = \sum_{n=0}^{4}[P_s(\tau)(1 - P_s(\tau))^n 2^{n-1} W] + (1 - P_s(\tau))^5 2^4 W. \quad (8)$$

The probability of a station perceives channel is idle for a DIFS interval and a select backoff countdown is $1 - P_B$. In this case, the station transits to the ATTEMPT state and the average waiting time equals to DIFS + $W/2$. The P_A is the probability that there is no arrival during the waiting period (the DIFS interval and the mean backoff time), and can be expressed as

$$P_A = e^{-\Lambda(\text{DIFS} + T_B)}. \quad (9)$$

When a station finishes its backoff countdown, it will transit into the ATTEMPT state without any delay; and then it tries to send the RTS frame. With probability P_s the transmitting station is successful and the time spent on handshake is T_s^2. Otherwise, with probability $1 - P_s$ the transmitting station fails with and a failed transition period of length T_c^2 caused. After a failure, the station transits to the BACKOFF state. Thus the success probability will be treated as a station successfully sends a RTS frame without colliding with other neighbors within τ seconds. Therefore, we have

$$P_s = e^{-\Lambda\tau}. \quad (10)$$

These assumptions preserve the validity of prior analytical results for the MAC delay of the IEEE 802.11 protocol [19].

4.2. Average delay

Now we can solve the expected average contention delay of a RTS/CTS handshake in the system (denoted as $\bar{D}$). From Fig. 7 we can obtain an expression for the average

MAC delay $\bar{D}$

$$\bar{D} = P_B(\bar{B}/2 + E_B) + (1 - P_B)(\mathrm{DIFS} + W/2 + E_A), \quad (11)$$

where E_B is the additional delay accumulated each time of a transmission spending in the BACKOFF state, and E_A is the delay caused by staying in the ATTEMPT state. The E_B can be derived by the following equation

$$E_B = P_A(\mathrm{DIFS} + T_B + E_A) + (1 - P_A)(\bar{B} + E_B) \quad (12)$$

and can be simplified as

$$E_B = \mathrm{DIFS} + T_B + E_A + \frac{1 - P_A}{P_A}\bar{B}. \quad (13)$$

And the expression for E_A is given by

$$E_A = P_s T_s^2 + (1 - P_s)(T_c^2 + E_B). \quad (14)$$

Substituting (13) into (14) leads to

$$E_A = P_s T_s^2 + (1 - P_s)\left(T_c^2 + \mathrm{DIFS} + T_B + E_A + \frac{1 - P_A}{P_A}\bar{B}\right). \quad (15)$$

Thus, we have

$$\begin{aligned} E_A &= T_s^2 + \frac{1 - P_s}{P_s}\left(T_c^2 + \mathrm{DIFS} + T_B + \frac{1 - P_A}{P_A}\bar{B}\right) \\ &= T_s^2 + \frac{P_s P_A - P_s - P_A + 1}{P_s P_A}\bar{B} \\ &\quad + \frac{1 - P_s}{P_s}(T_c^2 + \mathrm{DIFS} + T_B). \end{aligned} \quad (16)$$

Now substituting (16) into (13) leads to

$$\begin{aligned} E_B &= \mathrm{DIFS} + T_B + T_s^2 + \frac{P_s P_A - P_s - P_A + 1}{P_s P_A}\bar{B} \\ &\quad + \frac{1 - P_s}{P_s}(T_c^2 + \mathrm{DIFS} + T_B) + \frac{1 - P_A}{P_A}\bar{B} \\ &= \frac{1}{P_s}(\mathrm{DIFS} + T_B) + T_s^2 + \frac{1 - P_A}{P_s P_A}\bar{B} + \frac{1 - P_s}{P_s}T_c^2. \end{aligned} \quad (17)$$

Finally, we can get the average access delay $\bar{D}$ by substituting (16) and (17) into (11) and the equation will be

$$\begin{aligned} \bar{D} &= P_B\left[\bar{B}/2 + \frac{1}{P_s}(\mathrm{DIFS} + T_B) + T_s^2 + \frac{1 - P_A}{P_s P_A}\bar{B} + \frac{1 - P_s}{P_s}T_c^2\right] \\ &\quad + (1 - P_B)\left[\mathrm{DIFS} + W/2 + T_s^2 + \frac{P_s P_A - P_s - P_A + 1}{P_s P_A}\bar{B} \right. \\ &\quad \left. + \frac{1 - P_s}{P_s}(T_c^2 + \mathrm{DIFS} + T_B)\right]. \end{aligned} \quad (18)$$

Fig. 8 illustrates the expected contention delay derived by Eq. (18). We can see that, under a certain traffic load, the contention delay will become longer as more competitive stations are active in the network.

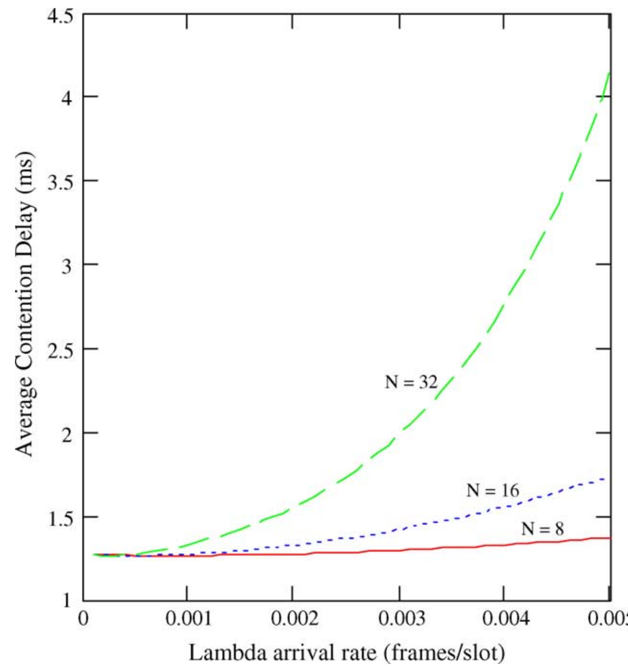


Fig. 8. The expected average contention delay ($\bar{D}$) in the CRI window under different number of stations (N=8, 16, and 32).

4.3. Approximate throughput

In this section, we analyze the numerical throughput of proposed MMA and MMA$^+$. From the results of the derived contention delay, we can compute the number of successful reservations in a given CRI. The average number of successful reservations, denoted as k, in CRI will be

$$k = \left\lceil \frac{\mathrm{CRI}}{\bar{D}} \right\rceil. \quad (19)$$

Based on value k, we can estimate the network throughput S, which is defined as the total quantity of successfully transmitted data over the capacity of all channel within the repetition cycle (RC). Let m be the mean length of the data frame. Then, the total quantity of transmitted data in the CFI is given by $k \cdot m$ and the throughput can be calculated as

$$S = \frac{k \cdot m}{\mathrm{RC} \times M} \times \text{data-rate}. \quad (20)$$

Note that the normalized throughput S used in this paper only includes pure data and could be called as *Goodput*.

In MMA, the RC consists of the CRI and CFI periods. Since they are non-overlapping to each other, the RC can be easily derived by equation RC=CRI+CFI. Assume all successful reservations are arranged to all channels ideally and there is no intersection occurrence on any source–destination pair. Thus the length of CFI in MMA will be

$$\mathrm{CFI} = \left\lceil \frac{k}{M} \right\rceil \times \mathrm{tp}, \quad (21)$$

where tp is the average transmission period of a request and is equal to $m+\tau+\text{SIFS}+\text{ACK}+\tau$.

In contrast with MMA, the repetition cycle in MMA$^+$ will be shorter than or equal to MMA by the overlapping feature. In other words, in MMA$^+$, the CRI and CFI in repetition cycle may partially or fully overlap each other. According to the operations of MMA$^+$, the RC is given by the following equation

$$\text{RC}=\begin{cases}\max\{\text{CRI},\text{tp}\}, & \text{if } k<M;\\ \left\lceil \dfrac{k}{M}\right\rceil\times\text{tp}+\text{CRI}, & \text{if } k\geq M \text{ and } k\%M=0;\\ \left\lfloor \dfrac{k}{M}\right\rfloor\times\text{tp}+\max\{\text{CRI},\text{tp}\}, & \text{otherwise.}\end{cases} \quad (22)$$

Fig. 9 compares the numerical analyses with the simulation results of the proposed MMA and MMA$^+$ under 2 Mb/s transmitting date rate. Each simulation sustains 600 s ($\approx 3\times 10^7$ slots) and each simulation result is derived by sampling 10 simulation runs with different random seeds. The analysis shows that MMA$^+$ will first reach the maximum throughput around 1.44 Mb/s when the CRI window size is about 85 slots (=1700 μs), $\lambda=30$ (frames/s/station), $N=16$ and $M=3$. Besides, MMA only reaches the maximum throughput around 1.1 Mb/s when the CRI window size is about 245 slots (=4900 μs). The simulation result of the MMA$^+$ protocol does not reach the maximum throughput calculated in the analysis section because the ideal arrangement of successful source–destination pairs in the CFI period is used in the analysis. By comparing the simulation results against the analytical results, we conclude that the MMA$^+$ with ECSA protocol is capable of obtaining the throughput near the ideal case. We also note that the saturated throughput of the MMA$^+$ protocol slightly decreases from 1.1 to 1.08 Mb/s. This result indicates that a longer CRI will scarify the channel utilization when the mean length is relatively small (e.g. 40 slots/frame). On the other hand, with a larger frame size, a longer CRI will derive a higher throughput. This phenomenon will be illustrated later.

From Figs. 10–13, we show a series of numerical results to depict the relationship of four variables N, λ, m, and M, and the influences to the throughput of the proposed MMA$^+$ protocol. In Fig. 10, we can see that the throughput of MMA$^+$ will get higher as the mean length of data frame gets larger. The maximal values of these curves are almost first appear in the CRI around 90 slots (=1800 μs).

The maximum throughput shown in Fig. 11 decreases when the network offer load $G=(N\times\lambda\times m)$/data rate increases. The performance of the MMA$^+$ protocol becomes lower as the offer load getting higher, since each station will suffer more contentions. As shown in Fig. 12, the throughput elevates as either the CRI or the frame length increases. The results also show that an obvious improvement can be obtained by enlarging the CRI window size

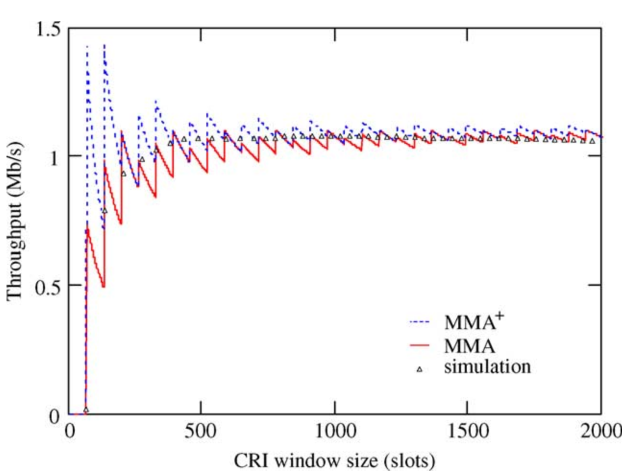


Fig. 9. Comparisons of throughput derived by proposed MMA, MMA$^+$ and analysis result under different CRI window sizes when $\lambda=30$, $N=16$, $M=3$, and $m=150$.

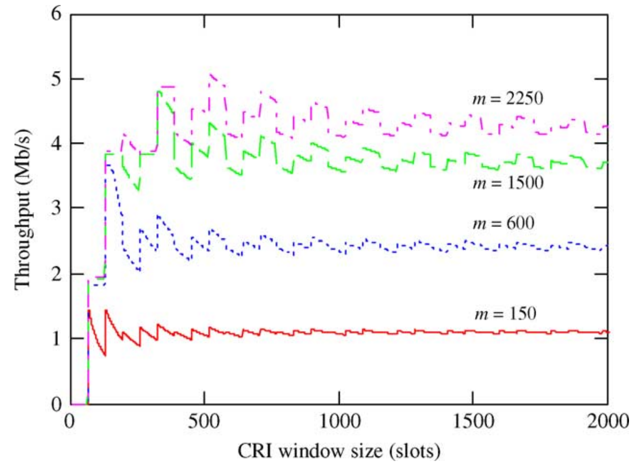


Fig. 10. Comparisons of throughput derived by proposed MMA$^+$ under different mean frame lengths and different CRI window sizes when $\lambda=5$, $N=32$, and $M=3$.

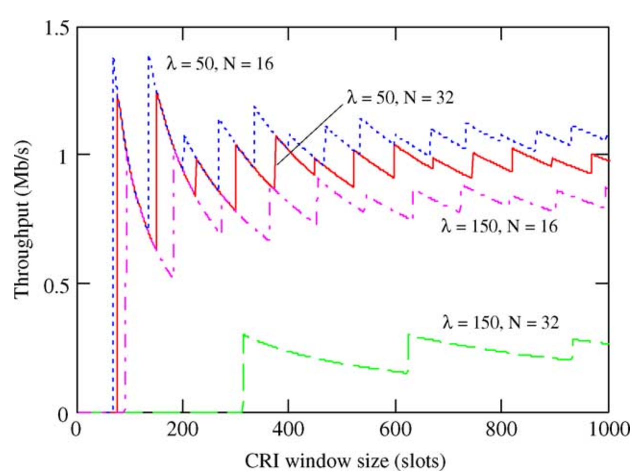


Fig. 11. Comparisons of throughput derived by proposed MMA$^+$ under different number of stations, different frame arrival rates, and different CRI window size when $M=3$ and $m=150$.

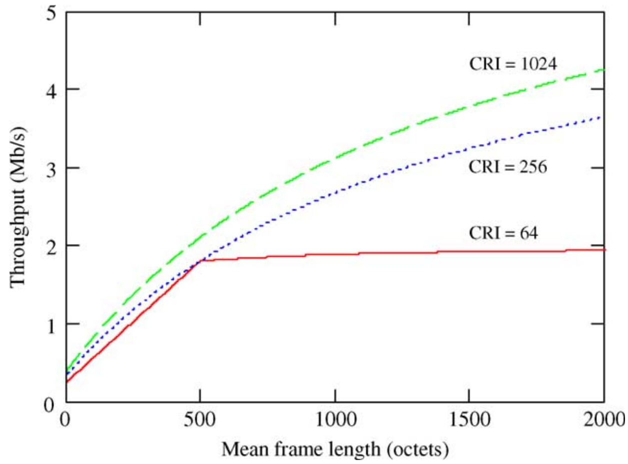


Fig. 12. Comparisons of throughput derived by proposed MMA$^+$ under different lengths of CRI and different mean frame lengths when $\lambda = 50$, $N = 16$, and $M = 3$.

when the frame length is relatively large. The reason is that more requests could be succeed in contention by extending CRI. If these requests have a longer transmission period, a longer CFI will be generated and a higher throughput will be derived. In another words, it is worthy to waste some bandwidth in CRI but obtaining higher channel utilization. Fig. 13 shows that the throughput increases as the number of usable channels increases. However, the throughput does not increase proportionally with the increasing number of available channels. From our observations, some channels are useless due to less active stations.

5. Simulation model

In order to evaluate the performance of the MMA and MMA$^+$ protocols, we also develop a detailed simulation model based on the distributed coordination function (DCF) of IEEE 802.11 WLANs [6]. In simulation runs, realistic system parameters (e.g. the direct sequence spread spectrum (DSSS) physical specification) as described in the IEEE 802.11 MAC protocol are used (parameters are listed in Table 1). The RTS/CTS exchange precedes data frame transmission and data frame are followed by an ACK. For simplicity, only unicast data frames are considered in simulation runs. The DCA [26] approach and the IEEE 802.11 protocol are also simulated for comparisons.

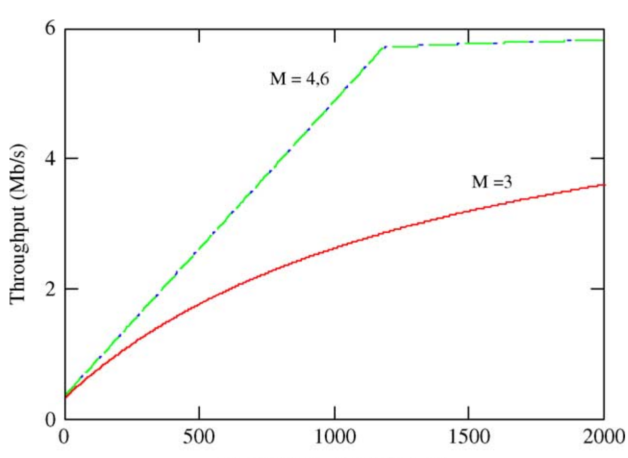


Fig. 13. Comparisons of throughput derived by proposed MMA$^+$ under different number of channels and different mean frame lengths when $\lambda = 50$, $N = 16$, and CRI $= 265$.

Table 1
System parameters in simulations

Parameter	Normal value
Channel bit rate	2 Mb/s
Transmission range	100 m
RTS frame length	160 bits (80 µs)
CTS frame length	112 bits (56 µs)
ACK frame length	112 bits (56 µs)
Preamble and PLCP header	192 bits (192 µs)
MAC header length	272 bits (136 µs)
A slot time	40 bits (20 µs)
SIFS	10 µs
ACWmin	31 slots
ACWmax	1023 slots
Air propagation delay (δ)	1 µs

Assume there are three independent channels in wireless network. Each mobile station in MMA, MMA$^+$, and IEEE 802.11 protocol has one transceiver and its radio transmission range is 100 m. On the other hand, each mobile station with DCA scheme equips two transceivers. The frame arrival rate of each mobile station follows the Poisson distribution with a mean λ, and the frame length is an exponential distribution with a mean of m octets [9,13], which including PHY and MAC header. Each simulation run lasts 600 s ($\approx 3 \times 10^7$ slots) and each simulation result is obtained by averaging the results from 10 independent simulation runs.

5.1. Simulation results

The simulation results are shown in Figs. 14–19, which depict the total throughputs (excluding the control overheads) derived by protocols DCA, MMA, MMA$^+$ and IEEE 802.11 CSMA/CA under different numbers of mobile stations N, different frame arrival rates λ (frames/s/station), different mean frame lengths m, different numbers of channels M, and different contention reservation intervals CRI.

Figs. 14 and 15 compare the throughput (in Mb/s) of four protocols in WLAN with multiple channels under different network loads when $N = 16$ and $m = 500$ octets. Fig. 14 demonstrates that the derived network throughput of three protocols (DCA, MMA and MMA$^+$) are linearly proportional with the frame arrival rate when the network load is overloaded. The IEEE 802.11 protocol first saturates when $\lambda \approx 20$ (and the network load is about $71.424\% = (N \times \lambda \times m)/(2\ \text{Mb/s}) = (16 \times 20 \times 500)/\ (2\ \text{Mb/s}))$ and

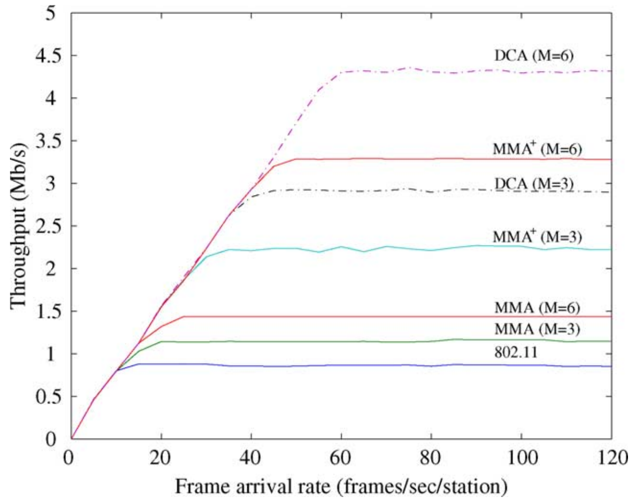


Fig. 14. Comparisons of throughput derived by MMA, MMA$^+$, DCA, and IEEE 802.11 protocols under different number of channels and different frame arrival rates when $N=16$, $m=500$, and CRI$=300$.

the maximal network throughput is about 1 Mb/s regardless of parameter M. On the contrary, MMA and DCA can easily achieve throughput up to 1.7 Mb/s even when $\lambda \approx 20$ and $M=3$. Furthermore, in the case of $M=3$, the maximum throughput of MMA$^+$ and DCA will, respectively, reach about 2.5 and 3.3 Mb/s. Undoubtedly, the significant network throughput gain is obtained from parallel transmissions on multiple channels. We also note that the MMA$^+$ can almost double the throughput of MMA because the channel wastage in both CRI and CFI are efficiently minimized in MMA$^+$. Moreover, MMA, MMA$^+$ and DCA will obtain a higher aggregate network throughput when more parallel channels are used; however, the throughput enhancement is getting smaller and smaller. This phenomenon is mainly caused by not enough active mobile stations as mentioned before. We also note that the throughput of

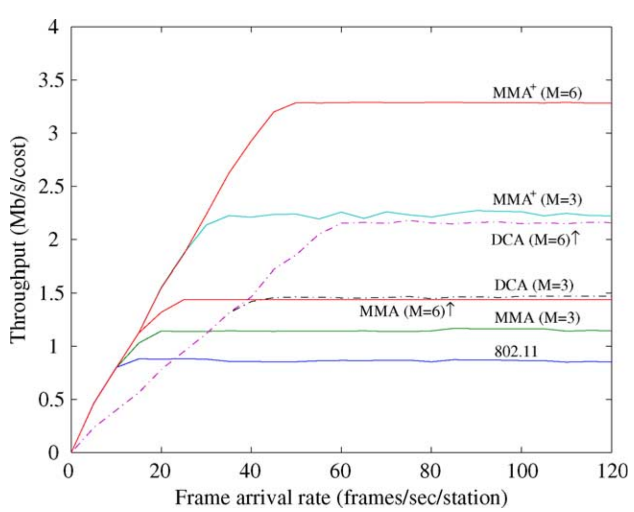


Fig. 15. Comparisons of cost-benefit derived by MMA, MMA$^+$, DCA, and IEEE 802.11 protocols under different number of channels and different frame arrival rates when $N=16$, $m=500$, and CRI$=300$.

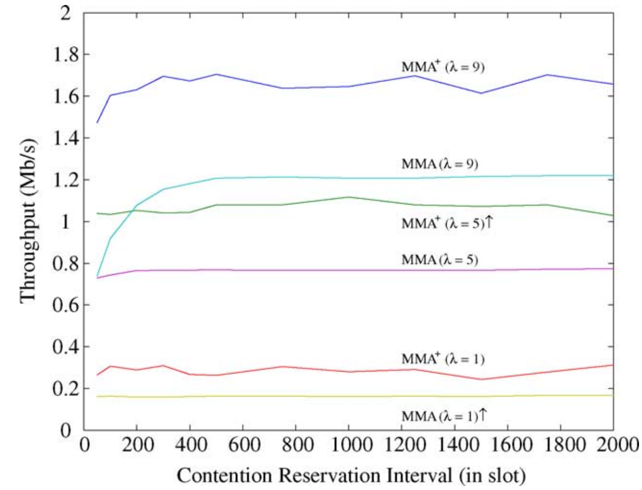


Fig. 16. Comparisons of throughput derived by MMA and MMA$^+$ protocols under different frame arrival rates and different contention window size when $M=3$, $m=150$, and $N=16$.

DCA outperforms MMA$^+$ about 132% when $M=3$ and $\lambda \geq 40$, and 127% when $M=6$ and $\lambda \geq 60$ (see Fig. 14). This is because that the MMA$^+$ is not smart enough to eliminate the bandwidth wastage in the repetition cycle, but DCA only wastes channel capacity in control channel. However, if we take the hardware cost into considerations, the MMA$^+$ outperforms DCA as illustrated in Fig. 15, where the derived throughput is the normalized throughput per transceiver. According to this result, we conclude that, under the single transceiver constrain, the MMA$^+$ can provide higher throughput than both the IEEE 802.11 protocol and DCA.

Fig. 16 demonstrates the relationships between the throughputs and the CRI window size. In both MMA and MMA$^+$, the maximal throughput varies with frame arrival rate. As the frame arrival rate is given higher, a higher

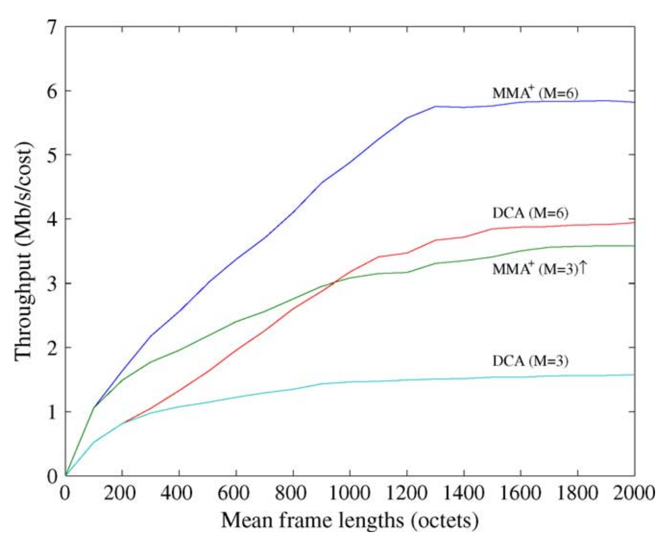


Fig. 17. Comparisons of throughput derived by MMA and MMA$^+$ protocols under different number of channels and different mean frame lengths when $\lambda=50$, CRI$=300$, and $N=16$.

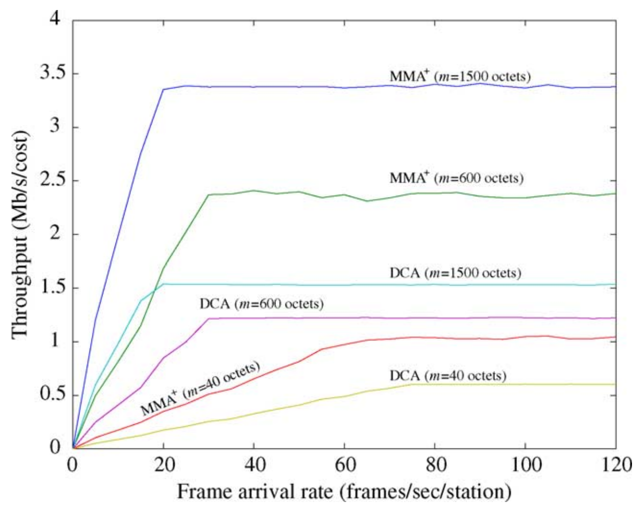


Fig. 18. Comparisons of throughput derived by MMA^+ and DCA protocols under different mean frame lengths and different frame arrival rates when $M=3$, CRI = 300, and $N=16$.

throughput will be achieved. It is worth mentioning that the maximal throughput first appears when CRI window size is set to be around 300 slots (also shown in Fig. 11) for all cases. From these results we conclude that the CRI window size can be set to a reasonable value to achieve the maximum network throughput; and we do not need a complex method to estimate the best CRI window size.

Fig. 17 illustrates how the network throughput is affected by the frame length and the number of available channels. In this simulation, the CRI window size is set as 300 slots, the frame arrival rate per each mobile station is 50 frames (heavy load) and the number of mobile stations is 16. In order to investigate the effect of frame length, different mean frame lengths, from 200 to 2000 octets, are simulated. From this figure, we can find that, given a longer mean frame length, a higher network throughput can be achieved using the MMA^+ and DCA protocols. Moreover, the maximal network throughput is proportional with the number of available channels. For example, the maximal network throughputs for MMA^+ in cases $M=3$ and $M=6$ are about 4.1 and 6.6 Mb/s, respectively. And, in the DCA scheme, the maximal normalized network throughputs in cases $M=3$ and $M=6$ are about 1.8 and 4.5 Mb/s, respectively. The throughput improvement, by increasing channel in both MMA^+ and DCA, is similar. However, in our opinions, the DCA uses two transceivers and should obtain a higher throughput gain comparing to MMA/MMA^+. We also conclude that the drawback of DCA is it does not have an efficient data scheduling method (likes CSA or ECSA) and is likely to waste the network bandwidth.

Fig. 18 illustrates how the network throughput per transceiver affected by the frame length and the frame arrival rate. In this simulation, the CRI window size is also set to 300 slots, $M=3$, and $N=16$. In order to investigate the effect of frame length, different mean frame lengths: 40, 600, and 1500 octets are considered. From this figure, we can find that given a longer mean frame length, a higher network throughput will be derived in MMA^+. The reason is that, when the CFI is relatively longer than CRI, long frames potentially reduce channel wastage. Again, we want to emphasize that the MMA^+ apparently outperforms DCA in terms of normalized throughput per transceiver.

Fig. 19 shows the service rate derived by MMA^+, DCA, IEEE 802.11 and DCA/cost under different loads when the CRI window size is 300 slots, $M=3$, $m=40$, and $N=16$. The service rate degrades when the network load is heavy. Note that the DCA scheme gets a higher service rate than the MMA^+ and IEEE 802.11 protocols, since DCA uses two transceivers to transmit packets. According to above simulation results, we conclude that, under the single transceiver constrain, the MMA^+ can provide higher throughput than both the IEEE 802.11 CSMA/CA protocol and DCA in IEEE 802.11 ad hoc multichannel WLAN.

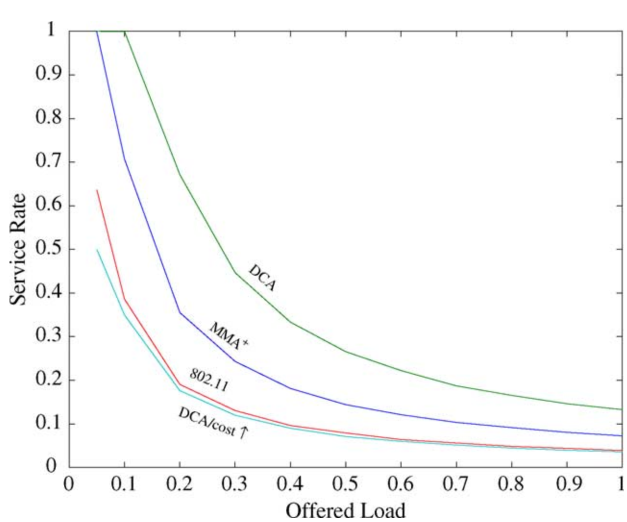


Fig. 19. Comparisons of service rate derived by MMA^+, DCA, and IEEE 802.11 protocols under different offered loads when $M=3$, $m=40$, CRI = 300, and $N=16$.

6. Summary and conclusions

In this paper, we propose a new CSMA protocol, *multichannel multiple access* (MMA), to support multichannel transmissions over IEEE 802.11 ad hoc WLANs in which every mobile station only equips with one transceiver. The channel scheduling algorithm (CSA) is also proposed to efficiently utilize channel capacities. The MMA protocol is compliant with the IEEE 802.11 Standard. All mobile stations running the MMA protocol will contend for channel access by using a dedicated channel during each periodical contention reservation interval; and then transmit data frames over different data channels. An enhanced MMA^+ protocol is also introduced to further minimize the bandwidth wastage. Simulation results showed that the proposed MMA^+ protocol with ECSA achieves an obviously higher normalized throughput than the conventional IEEE 802.11 CSMA/CA protocol and the DCA scheme.

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