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A dynamic adjustable contention period mechanism and adaptive backoff process to improve the performance for multichannel mesh deterministic access in wireless mesh LAN

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Abstract

IEEE802.11s draft proposes a new medium access control function-mesh deterministic access (MDA), which is mainly used for single-channel wireless mesh local area network (LAN). In single-channel environment, collisions between control packets and data packets may occur very often. To completely avoid the collision between control packets and data packets, the mesh delivery traffic indication message (DTIM) interval is first divided into contention period and data transmission period. To reduce the hardware requirements in design, we require a mesh point (MP) only equips a single transceiver to support multichannel environment. To provide higher performance and network capacity than the original MDA for wireless mesh LAN, we proposed a multichannel MDA (MMDA) algorithm. However, the MMDA algorithm may suffer from the resource waste problem when wireless mesh LAN is at heavy-loading situation, so this paper proposes a dynamic adjustable contention period (DACP) mechanism to solve this problem. In addition, we use an adaptive backoff process (ABP) to improve the fairness of the MMDA algorithm. The theoretical analysis gives the upper limit of the throughput for the DACP mechanism. The simulation experiments clearly show the results in multichannel wireless mesh LAN environment that the proposed scheme performs better than the MMDA algorithm and the enhanced distributed channel access (EDCA) in throughput, average waiting time, and packet drop ratio.

Keywords: IEEE802.11s; Medium access control; Mesh deterministic access; Wireless mesh LAN

1 Introduction

With the popularity of wireless local area network (LAN), increasing the network coverage is the necessary development. IEEE802.11s draft [1] divides nodes into two categories, including mesh node and non-mesh node. A mesh node can support mesh services, but non-mesh node cannot, e.g., the original IEEE802.11 station (STA) is a non-mesh node [2]. Mesh nodes are divided into two categories: mesh point (MP), which only supports mesh services such as route selection and packet forwarding; mesh access point (MAP), which provides access point (AP) functions for STAs and mesh services. For compatibility with the IEEE802.11 LAN, wireless mesh LAN must be able to link with other networks; therefore, a mesh

point portal (MPP) provides the functions of layer 2 bridge and layer 3 interworking [3]. Wireless mesh LAN topology can be mainly divided into 802.11 connected mesh and 802.11 mesh *ad hoc* [4]. In IEEE802.11s draft, the medium access control (MAC) layer protocol has great influence for wireless mesh LAN performance [5,6] and it follows the original IEEE802.11e enhanced distributed channel access (EDCA) [7], including congestion control [8,9], power saving [10], synchronization [11] and beacon collision avoidance [12], and quality of service (QoS) [13-15].

IEEE802.11s draft proposes the mesh deterministic access (MDA) in the MAC enhanced region [16]. MDA mainly works in the single-channel network, and the related works of MDA also focuses on the improvement of single-channel network performance. The authors of [17] propose a semi-random backoff (SRB) method that enables resource reservation. Cheng et al. propose the DPSO-CA

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algorithm to assign channel with topology preservation in multiradio wireless mesh networks [18]. Xiao et al. investigate the fundamental performance limits of MAC protocols for particular multihop sensor networks [19]. Vishnevsky et al. make the beacons responsible for supporting MDA designed for delay-sensitive multimedia applications [20]. The authors of [21] develop a scheduled mesh access (SMA) mechanism based on MDA, while SMA has better anti-interference ability than EDCA. The authors of [22] define the MDA interframe space (MIFS) to make MP get higher priority to access its own MDA opportunity (MDAOP). However, single-channel network environment has higher collision probability and cannot avoid collisions between control packets and data packets. In particular, network performance is strictly limited in the single-channel wireless mesh LAN when it is in the heavy-loading situation and hidden node environment. According to [23,24], using multichannel architecture is more effective than single-channel architecture to enhance performance and reduce collision probability in IEEE802.11 network. Nezhad et al. [25] shows some channel assignment (CA) to improve wireless mesh network performance by limiting the negative interference effects. The authors of [26] give the embedded version FreeBSD for multichannel wireless mesh networks. Ku et al. [27] proposes a traffic-aware switching scheme (TRASS) for wireless mesh network. In order to further enhance wireless mesh LAN performance and capacity, we have proposed multichannel MDA (MMDA) algorithm to make MDA works on multichannel wireless mesh LAN [28,29]. The MMDA algorithm adopts four-way handshaking mechanism to reduce hidden node problems, and mesh delivery traffic indication message (DTIM) interval is divided into contention period (CP) and data transmission period (DTP) to completely avoid the collision between control packets and data packets. The MMDA algorithm is designed with only single transceiver, so it can reduce the hardware requirements and design complexity.

The goals of this paper are to improve the MMDA algorithm and to enhance the performance of the multichannel wireless mesh LAN. The MMDA algorithm uses a fixed contention period mechanism, so it causes the network resource waste problem when wireless mesh LAN is in high-loading situation. This paper proposes a dynamic

adjust contention period (DACP) mechanism to solve the abovementioned problem. Besides, the MMDA algorithm uses contention to reserve MDAOPs; hence, some MPs may reserve more MDAOPs than the other MPs, which cause unfairness. Therefore, this paper further adopts an adaptive backoff process (ABP) to improve fairness. The organization of this paper is as follows: the next section is background description; Section 3 is to describe the proposed schemes; Section 4 analyzes the throughput of the DACP mechanism; Section 5 shows the simulation results; and finally, Section 6 concludes the paper.

2 Background description

In the original MDA, a mesh DTIM interval is defined between two consecutive beacon frames. According to IEEE802.11s draft, the slot size of mesh DTIM interval is set to 32 μ s, in which an MP can reserve MDAOP to transmit data. An MDAOP can be reused in every mesh DTIM interval until an MP finishes transmission and releases it. MDA is established by using two control packets: *MDA setup request* and *MDA setup reply*. Figure 1 shows the operation of MDA mechanism. Before a source MP (MP_A) transmits data, it sends MDA setup request packet to its destination MP for requesting MDAOP setup. If the destination MP (MP_B) successfully received MDA setup request packet and can satisfy the request of MDAOP setup, it will reply MDA setup reply packet to the source MP. Then, MDA mechanism is completed, so the source MP can build a MDAOP on selected location of mesh DTIM interval with the destination MP and periodically use this MDAOP to transmit data. However, MDA mechanism in IEEE802.11s draft is optional, and it means that not every MP in wireless mesh LAN should support MDA mechanism.

MMDA splits the mesh DTIM interval into CP and DTP as shown in Figure 2. In CP, MPs use contention mechanism to reserve MDAOP, and the successful MP establishes MDAOP at the selected channel to transmit data in DTP. It is to make sure that control packets and data packets can be transmitted in different intervals and avoid the collisions between them. Because MMDA algorithm allows an MP only equips a single transceiver in wireless mesh LAN, only a channel (i.e., CH_1) is listened by all MPs in CP; then, all MPs know the channel

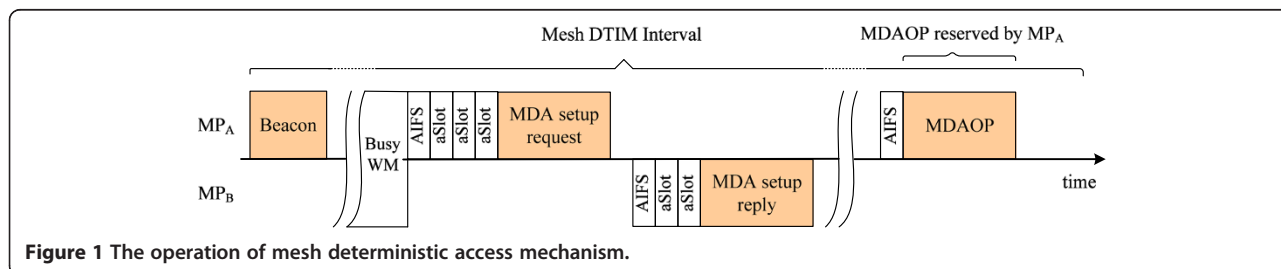
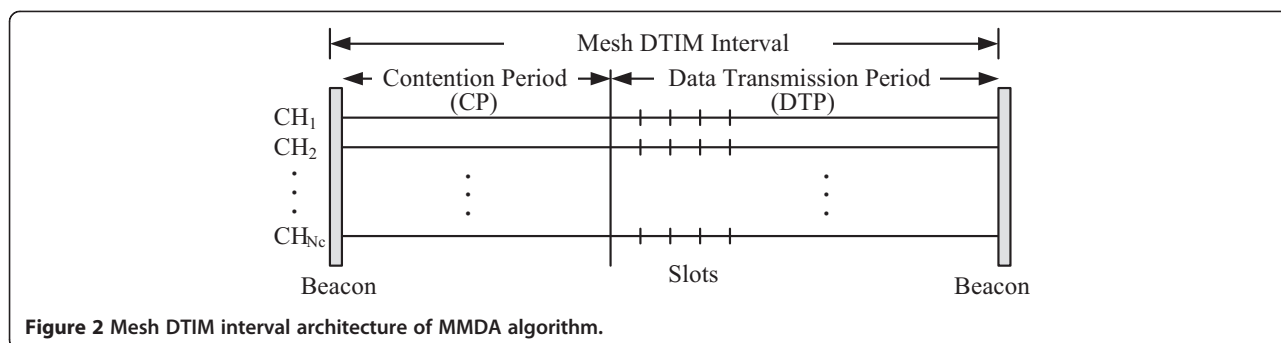


Figure 1 The operation of mesh deterministic access mechanism.



information in DTP, but CH_1 can also be used to transmit data in DTP. The maximum size of an MDAOP to be reserved in DTP is 4,096 μ s (or 128 slots), which can be used by MP periodically at the same location of each DTP.

In order to make MPs achieve timing synchronization in wireless mesh LAN, we use the IEEE802.11 *ad hoc* timing synchronization mechanism [30] because the MMDA algorithm uses the new defined mesh DTIM interval architecture. An MP sends a beacon in accordance with the principles of the distributed coordination function (DCF) at the beginning of each beacon interval; the other MPs will cease sending beacons and take the timestamp values in the beacons if any MP sends beacon successfully. To use the MMDA algorithm, we require that each MP must build a neighbor MP status table (NMST) to make sure that each MP knows its neighbor MPs' status and channel state information, including the MP's identification (ID), channel ID currently used by the MP, offset from MDAOP's starting position to the beginning of sub-interval, duration of MDAOP, periodicity (i.e., the number of MDAOPs in DTP), and MP supported for MDA mechanism or not. For example, if periodicity is four, it means that DTP is divided into four subintervals, while the four MDAOPs are located in the same distance from the beginning of these four subintervals.

Similarly as the original IEEE802.11 *ad hoc* networks, wireless mesh LAN also has hidden node problem [31]. In order to effectively solve this problem, the MMDA algorithm uses four-way handshaking mechanism instead of two-way handshaking mechanism in the original MDA. In other words, the MMDA algorithm uses four control packets, including MDA setup request, MDA

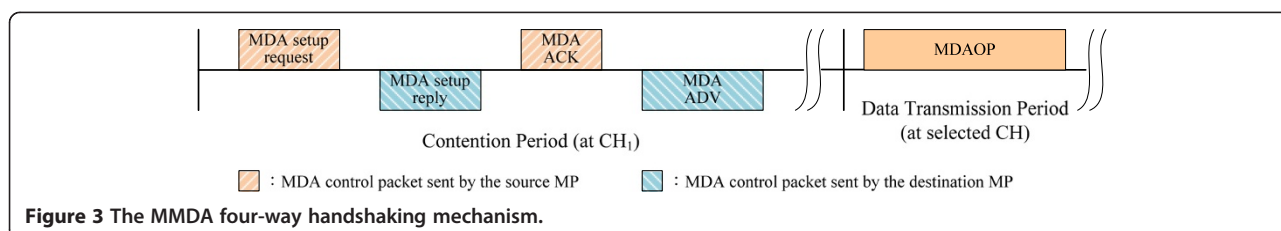
setup reply, *MDA ACK* (acknowledge), and *MDA ADV* (advertisement), to reserve MDAOP. By the additional MDA ACK and MDA ADV, the MMDA algorithm can alleviate hidden node problem in wireless mesh LAN. The procedure of the MMDA four-way handshaking mechanism is shown in Figure 3. The proposed scheme in this paper also follows four-way handshaking mechanism of the MMDA algorithm.

The MMDA algorithm allows an MP to reserve different MDAOPs to transmit data on the same channel or different channels in DTP, if MP needs more than one MDAOP to meet the transmission request. Figure 4 shows an example of the multiple MDAOPs (included MDAOPs' offsets and durations) used by MP_A on different channels (CH_4 and CH_5) in DTP, and Table 1 shows that the NMST records the corresponding information of MDAOPs for this example.

The MMDA algorithm has two MDAOP selection mechanisms: the channel load first random fit (CLFRF) and the multichannel best fit (MCBF) mechanisms. The CLFRF mechanism is to randomly select duration from the lightest loading channel for MDAOP reservation, which has the advantage of simple and no more complex operation. The MCBF mechanism is to find the best fit location from all channels to build the requested MDAOP, i.e., the MCBF mechanism is to select the minimum duration from these durations; hence, the advantage of the MCBF mechanism is that the remaining space can be minimized after building MDAOP to avoid causing a large fragmentation.

3 Dynamic adjustable contention period mechanism and adaptive backoff process

The MMDA algorithm uses the fixed ratio of CP and DTP in the mesh DTIM interval, which enables MP to



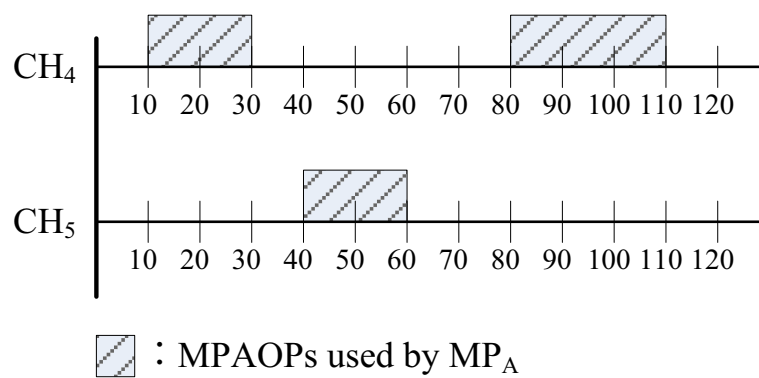


Figure 4 The example of the multiple MDAOPs used by MP_A on different channels in DTP.

efficiently reserve enough MDAOPs in CP to transmit data. The available duration to establish MDAOPs in DTP will be almost reserved, if a wireless mesh LAN becomes heavily loaded. In addition, the holding time of the reserved MDAOP will increase, if the MDAOP owner needs to send a large amount of data by its reserved MDAOP periodically; therefore, the teardown ratio of MDAOPs in the wireless mesh LAN becomes seriously small, where teardown means MP must release the occupied MDAOP when it completes the transmitting data. An MP cannot find the available duration in DTP to establish MDAOP because each channel in DTP may be almost unable to provide the available duration. In this situation, MP will not send MDA setup request in CP, and the times by using four-way handshaking mechanism to reserve MDAOP will be significantly reduced in CP. The wasting resource problem may occur and cause the performance unable to further increase for wireless mesh LAN. In Figure 5, the shaded region in CP shows the wasted network resource of the MMDA algorithm. Therefore, the DACP mechanism and ABP are to solve for it and described as follows:

3.1 Dynamic adjustable contention period mechanism

The advantage of DACP mechanism is that it can further improve the capacity and performance of wireless mesh LAN in a heavy-loading situation. DACP mechanism allows MP to adjust CP ratio and increase DTP ratio in the mesh DTIM interval for sending more data when DTP is at the saturated condition. First, we define that MP may have three different MP types: normal contention

period (NCP), enable contention period shorten (ECPS), and demarcation point (DP). NCP means that an MP maintains the original CP and DTP ratios in the mesh DTIM interval, while ECPS means that an MP shortens CP to increase the available duration in DTP because DTP has been saturated. The NCP MPs and ECPS MPs may cause the collisions between control packets and data packets when they communicate with each other because of different CP ratios. A DP is defined for the intermediate between NCP and ECPS, which means that the neighbor MPs of an ECPS MP should be the ECPS or DP type, and the neighbor MPs of an NCP MP should be the NCP or DP type. The duration in DP includes the shortened CP, the original DTP, and the additional period. Therefore, the DP MP has the following restrictions: (1) the DP MP in additional period can only receive control messages issued by its neighboring MPs to update NMST, and (2) the NCP or ECPS MP cannot reserve MDAOPs with a DP MP in additional period. The architectures of the mesh DTIM interval for these three types are different as shown in Figure 6, while Table 2 shows the three MP types' ratios of CP and DTP, where we assume that X and Y represent the original CP ratio of MMDA algorithm and the shortened CP ratio in the mesh DTIM interval. DACP mechanism allows MP to transfer among these three types according to its own situation and adjust the CP ratio of the mesh DTIM interval. The available duration which DTP gets from the shortened CP is called additional period. For example, the ECPS MP's DTP is the sum of the original DTP and the additional period.

In general, an MP uses the four-way handshaking mechanism of MMDA algorithm to reserve MDAOPs. An MP may determine to start the DACP mechanism as the network becomes heavy loading, i.e., if the utilization of DTP reaches almost saturated, and this situation remains over a certain duration (e.g., ten mesh DTIM intervals). Then, the MP sends a contention period change (CPC) request packet to its neighbor MPs and waits for the neighbor MPs' CPC reply packets to do the state

Table 1 The NMST record of the corresponding information of MDAOPs in Figure 4

MP ID	Channel ID	Offset	Duration	Periodicity	MDA support
MP_A	4	10	20	1	1
MP_A	5	40	20	1	1
MP_A	4	80	30	1	1

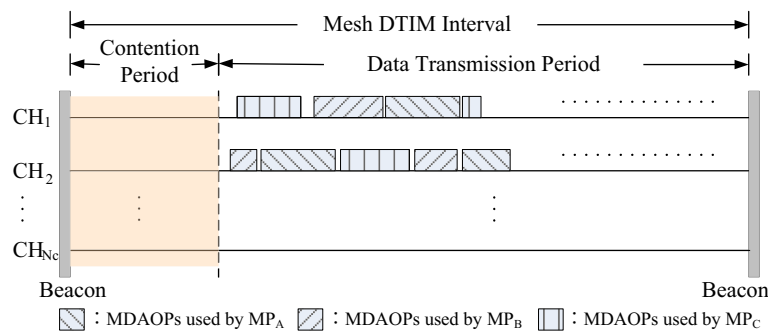


Figure 5 Network resource waste problem of MMDA Algorithm.

transition. The related state transition diagram for these three different types is shown in Figure 7 with the actions marked from A to K, where pre-NCP, pre-DP, and pre-ECPS represent the three transient states before MP entering the NCP, DP, and ECPS states, respectively. The functions of the actions are summarized as the following:

A. The NCP MP records the information and replies the CPC reply packet when it receives the CPC request packet of NCP or DP type.

- B. The NCP MP enters pre-ECPS state when the saturated situation occurs. It continues to send the CPC request packet of ECPS type until receiving all neighbor MPs' CPC reply packets.
- C. The pre-ECPS MP enters the ECPS state in the next mesh DTIM interval, when it receives all neighbor MPs' CPC reply packets.
- D. The NCP MP replies the CPC reply packet and enters the pre-DP state, when it receives the CPC request packet of ECPS. The pre-DP MP continues

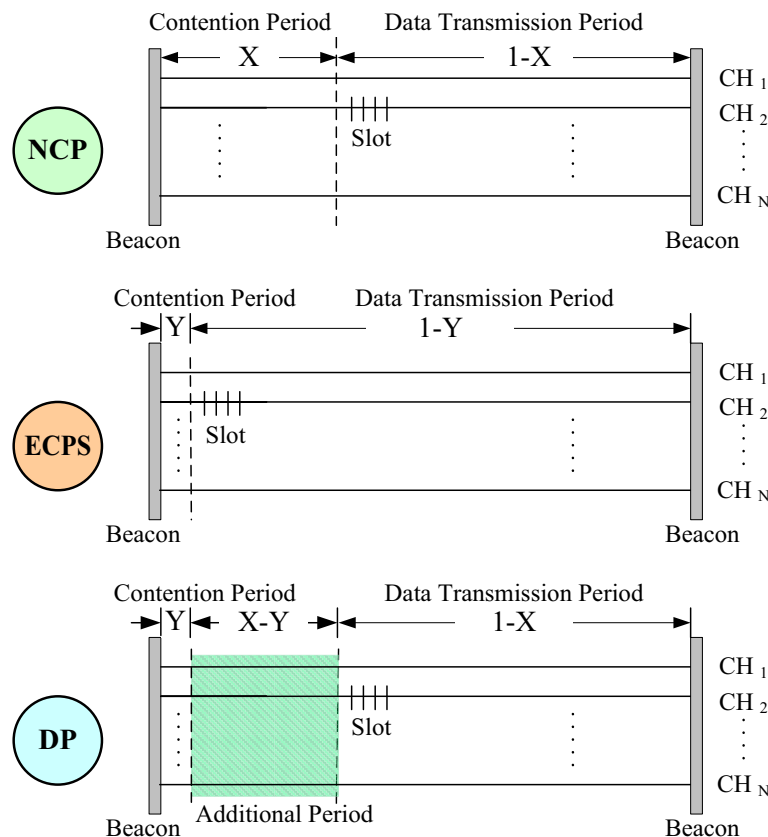


Figure 6 Mesh DTIM interval architecture of the three different MP types.

Table 2 The ratios of CP and DTP in the different MP types

Type	Mesh DTIM interval architecture
NCP	CP ratio : X , DTP ratio : $1 - X$
ECPS	CP ratio : Y , DTP ratio : $1 - Y$
DP	CP ratio : Y , additional period ratio : $X - Y$, DTP ratio : $1 - X$

to send CPC request packet of DP type until receiving all neighbor MPs' CPC reply packets.

- E. The pre-DP MP enters the DP state in the next mesh DTIM interval, when it receives all neighbor MPs' CPC reply packets.
- F. The ECPS MP records the information and replies the CPC reply packet, when it receives the CPC request packet of ECPS or DP type.
- G. The ECPS MP enters the pre-DP state, when the utilization of DTP is less than the high-loading situation for more than the limit number of mesh DTIM intervals, and there is no MDAOP in the additional period. It continues to send the CPC request packet of DP type until receiving all neighbor MPs' CPC reply packets.
- H. The DP MP enters the pre-ECPS state, when the saturated situation occurs. It continues to send the CPC request packet of ECPS type until receiving all neighbor MPs' CPC reply packets.
- I. The DP MP enters the pre-NCP state, when all DP MP's neighbor MPs are not ECPS type and the utilization of DTP is less than the high-loading situation for more than the limit number of mesh DTIM intervals. It continues to send the CPC request packet of NCP type until receiving all neighbor MPs' CPC reply packets.

- J. The pre-NCP MP enters the NCP state in the next mesh DTIM interval, when it receives all neighbor MPs' CPC reply packets.
- K. The DP MP records the information and replies the CPC reply packet, when it receives any type of CPC request packet.

To further explain the operations of the DACP mechanism, we describe the state transition diagrams as shown in Figure 7 for the MP at the states of NCP, ECPS, and DP, respectively. First, we assume that the MP starts at the NCP state, it may stay at the NCP state by action A; it may go to the pre-ECPS state by action B and then arrive at the ECPS state by action C; or it may go to the pre-DP state by action D and then arrive at the DP state by action E. Then, we assume that the MP starts at the ECPS state, it may stay at the ECPS state by action F; or it may go to the pre-DP state by action G and then arrive at the DP state by action E. Similarly, we assume that the MP starts at the DP state, it may stay at the DP state by action K; it may go to the pre-ECPS state by action H and then arrive at the ECPS state by action C; or it may go to the pre-NCP state by action I and then arrive at the NCP state by action J.

3.2 Adaptive backoff process

Before an MP starts contention to reserve MDAOP in CP, it first enters backoff procedure according to CSMA/CA in IEEE802.11 standard. After waiting for a random time, the source MP sends MDA setup request packet to the target MP. Because the MMDA algorithm uses the contention mechanism to reserve MDAOPs, an MP may reserve more MDAOPs than the other MPs and result in unfairness problem. The contention window (CW) size may play an essential role in improving fairness [32]; therefore, ABP is to adjust the backoff time parameters according to the number of MDAOPs owned by an MP, which allows the MP having less MDAOPs may have higher probability to reserve MDAOPs.

According to NMST, an MP knows the neighbor MPs' MDAOPs and decides to change the backoff time or not by comparing its own MDAOPs' duration and the average durations of the neighbor MPs' MDAOPs. In other words, ABP uses the evaluation parameter r to decide if the MP needs to adjust the backoff time parameters or not as shown in (1), where $MDAOP_{own}$ and $MDAOP_{avg}$ represent the durations of MDAOPs reserved by the MP itself and the neighbor MPs, respectively. According to the value r , ABP defines four access categories (AC), $AC_0 \sim AC_3$, with different arbitration interframe space number (AIFS_N), CW_{min} , and CW_{max} as shown in Table 3. Then, the MP can get the corresponding backoff time parameters to derive the new backoff time by (2).

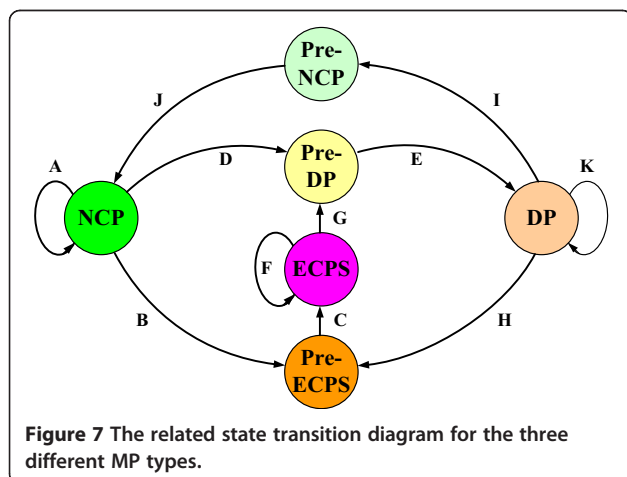


Table 3 The backoff time parameters of ABP

AC	r value	AIFSN	CW _{min}	CW _{max}
AC ₀	r=0	2	7	31
AC ₁	0 < r < 0.5	2	15	63
AC ₂	0.5 ≤ r < 1	2	31	127
AC ₃	r ≥ 1	2	63	255

The advantage of ABP is that it can enhance fairness between MPs in wireless mesh LAN.

$$r = \frac{\text{MDAOP}_{\text{own}}}{\text{MDAOP}_{\text{avg}}} \quad (1)$$

$$\text{Backoff_Time[AC]} = \text{Random}(0, \text{CW[AC]}) \times \text{aSlotTime} \quad (2)$$

4 Analysis of DACP mechanism in throughput

In this section, we analyze the MMDA algorithm with the DACP mechanism based on the saturated contention in CP. We assume that there are n MPs operated in CP with the saturation mode; we only consider the two-hop wireless mesh LAN environment to simplify the analysis. We assume that there are totally n MPs operated in CP with the saturation mode binary exponential backoff (BEB). Let us denote W_0 be the initial contention window, while p_t and p_c are the probabilities of the MP transmission and the collisions caused by at least one of $n - 1$ MP transmissions, respectively, which can be obtained by (3) [33], where MPs contend with each other until successful transmission in CP without limiting the maximum backoff stage. p_t can also be obtained by (4).

$$p_t = \frac{2(1-2p_c)}{W_0(1-p_c) + 1-2p_c} \quad (3)$$

$$p_t = 1 - (1-p_c)^{1/(n-1)} \quad (4)$$

We can easily obtain the unique solutions of p_t and p_c , respectively, by solving (3) and (4), if n and W_0 are given. In addition, $p_t(n)$ and $p_c(n)$ can be considered as the functions of n for p_t and p_c , respectively, by assuming W_0 is a fixed system parameter. Therefore, the probabilities of successful transmission and idle channel can also be considered as a function of n and expressed by (5) and (6), respectively. Let p_{coll} represent the collision probability caused by two or more MP transmissions at the same time, and $p_{\text{coll}}(n)$ is the function of n for p_{coll} as shown in (7). Similarly, we consider the other parameters as the functions of n later in this paper.

$$p_{\text{succ}}(n) = np_t(n)(1-p_t(n))^{n-1} \quad (5)$$

$$p_i(n) = (1-p_t(n))^n \quad (6)$$

$$p_{\text{coll}}(n) = 1-p_i(n)-p_{\text{succ}}(n) \quad (7)$$

According to the content of NMST, MP knows the durations will be used in DTP and avoids selecting these durations; then, MP can reserve MDAOP by completing the MMDA four-way handshaking mechanism. Let us denote T_{cp} to be the duration of CP, which obviously affects the number of successful contentions in CP. Let us also denote T_{cp_c} to be the critical duration of CP, which is the minimum duration of CP for MPs to successfully reserve all available MDAOPs. Let us assume that an MP will experience i times of collision and j empty slot times before successfully reserving an MDAOP in CP with n MPs to contend, whose joint probability mass function, $P_{ss}(i, j, n)$, can be obtained by (8), where I and J are the random variables that an MP will experience i times of collision and j empty slots before successfully reserving an MDAOP in CP, respectively. Furthermore, the means of I and J can be expressed as the functions of n and obtained by (9) and (10), respectively.

$$\begin{aligned} p_{ss}(i, j, n) &= p[I = i, J = j] \\ &= \binom{i+j}{j} p_{\text{coll}}^i(n) p_i^j(n) p_{\text{succ}}(n), \text{ for } i \\ &= 0, 1, 2, \dots \text{ and } j = 0, 1, 2, \dots \end{aligned} \quad (8)$$

$$\bar{I}(n) = \sum_{i=0}^{\infty} i \times \sum_{j=0}^{\infty} p_{ss}(i, j, n) \quad (9)$$

$$\bar{J}(n) = \sum_{j=0}^{\infty} j \times \sum_{i=0}^{\infty} p_{ss}(i, j, n) \quad (10)$$

Let us denote T_s and T_c to be the durations of each successful MMDA four-way handshaking contention and collision as shown in (11) and (12), respectively, where T_{MDASRQ} , T_{MDASRP} , T_{MDAACK} , T_{MDAADV} , T_{DIFS} , and T_{SIFS} are the durations of MDA setup request, MDA setup reply, MDA acknowledge, MDA advertisement, DIFS, and SIFS, respectively. Let us define $T_r(n)$ as the average time to reserve an MDAOP for an MP in CP, which can be obtained by (13), where T_i is a slot time that should be long enough to access the channel state information. Let us denote T_{DTIM} and T_{DTP} to be the durations of the mesh DTIM interval and data transmission period, respectively, where T_{DTP} can be obtained by (14).

$$T_s = T_{\text{MDASRQ}} + T_{\text{MDASRP}} + T_{\text{MDAACK}} + T_{\text{MDAADV}} + T_{\text{DIFS}} + 3T_{\text{SIFS}} \quad (11)$$

$$T_c = T_{\text{MDASRQ}} + T_{\text{DIFS}} \quad (12)$$

$$T_r(n) = \bar{I}(n) \times T_c + \bar{J}(n) \times T_i + T_s \quad (13)$$

$$T_{DTP} = T_{DTIM} - T_{cp} \quad (14)$$

Let us denote N_a to be the available MDAOPs provided for MPs to reserve in DTP as shown in (15), where N_c , B , D , and L are the number of channels in wireless mesh LAN, each channel's bandwidth, MDAOP duration, and the average interval between two MDAOPs in DTP, respectively. Let us define N_{\min} as the minimum value of n and N_a ; then, the critical duration of CP $T_{cp-c}(n)$ can be obtained by (16). Hence, the available MDAOPs will be completely reserved by MPs within CP, if T_{cp} is longer than T_{cp-c} . Let us define T_m as the m th subcritical duration of CP that m MPs can successfully reserve MDAOPs, which can be obtained by (17). We define $G(n)$ as the number of MPs that can successfully reserve MDAOPs in a CP, which can be obtained by (18). Finally, the average throughput of the NCP MP, $S_{NCP}(n)$, can be obtained by (19).

$$N_a = \left\lfloor \frac{T_{DTP} \times B}{D + L} \right\rfloor \times N_c \quad (15)$$

$$T_{cp-c}(n) = \sum_{x=0}^{N_{\min}} T_r(n-x) \quad (16)$$

$$T_m(n) = \sum_{x=0}^{m-1} T_r(n-x), \text{ for } 1 \leq m \leq N_{\min} \quad (17)$$

$$G(n) = \min(n, m) \quad T_{cp} \in [T_m, T_{m+1}), \text{ for } m = 0, 1, \dots, N_{\min-1} \quad (18)$$

$$S_{NCP}(n) = \frac{G(n) \times D}{T_{DTIM}} \quad (19)$$

Next we analyze the throughput for the ECPS MP. An MP will enter the ECPS state and shorten the CP of the mesh DTIM interval if DTP becomes saturated. Let us define T_{cp-s} and T_{ap} to be the shortened CP and the duration of the additional period, respectively. Let us also define N_{ap} to be the available MDAOPs provided for MPs to reserve in the additional period, which can be obtained by (20). The shortened CP ratio $T_{cp-s}(n)$ can be obtained by (21). Let denote $G_s(n)$ be the number of MPs that can successfully reserve MDAOPs in an additional period, if T_{cp-s} is long enough for MPs to reserve the available MDAOPs in additional period, which can be obtained by (22). Finally, the throughput of the ECPS MPs, $S_{ECPS}(n)$, can be obtained by (23).

$$N_{ap} = \left\lfloor \frac{T_{ap} \times B}{D + L} \right\rfloor \times N_c \quad (20)$$

$$T_{cp-s}(n) = \sum_{x=0}^{N_{ap}} T_r(n-x) \quad (21)$$

$$G_s(n) = G(n) + N_{ap} \quad (22)$$

$$S_{ECPS}(n) = \frac{G_s(n) \times D}{T_{DTIM}} \quad (23)$$

5 Simulation experiments

In this section, simulation has been executed by using C# program. We consider the wireless mesh LAN topology in a random style, which consists of 32 MPs placed in 250×250 m region. We assume that all MPs are fixed with the traffic type of constant bit rate (CBR), regardless of background noise and propagation delay. We also assume that the original CP ratio (X) and the shortened CP ratio (Y) are 30% and 5%, respectively. The other simulation parameters are listed in Table 4.

The simulation experiments show for the performance in average throughput, average waiting time, packet drop ratio, fairness, and collision ratio, which are defined in (24) to (28), respectively. In (24), Pkt_b , s , T , and M represent the total number of the transmitted packets by MP_{*b*}, packet size, total simulation time, and total number of MPs, respectively. In (25), Tx_Pkt , Tl_i , and Ta_i represent the total success transmitted packets, the times that the i th packet leaves and enters the queue, respectively. In (26), Pkt_g and Pkt_d represent the total numbers of generated and dropped packets, respectively. In (27), S_i represents the throughput of MP_{*i*}. In (28), $N_{coll,i}$ and $N_{cont,i}$ represent the total numbers of collisions and contentions occurred at MP_{*b*}, respectively.

$$\text{Average throughput} = \frac{\sum_{i=1}^n Pkt_i \times s}{n \times T} \quad (24)$$

$$\text{Avg_waiting}_{\text{time}} = \frac{\sum_{i=1}^{Tx_Pkt} [Tl_i - Ta_i]}{Tx_Pkt} \quad (25)$$

Table 4 The simulation parameters

Parameter	Value
Number of MPs	32
Slot time	32 μ s
Mesh DTIM interval	100 ms
Packet size	512 bytes
MP transmission range	60 m
Number of channels	3
Channel capacity	2 Mbps
dot11MeshRetryTimeout	500 ms
dot11MeshMaxRetries	6
Simulation time	100 s

$$\text{Packet_drop_ratio} = \frac{\text{Pkt}_d}{\text{Pkt}_g} \quad (26)$$

$$\text{Fairness_index} = \frac{\left(\sum_{i=1}^n S_i\right)^2}{n \times \sum_{i=1}^n (S_i)^2} \quad (27)$$

$$\text{Collision_ratio} = \frac{\sum_{i=1}^n N_{\text{coll},i}}{\sum_{i=1}^n N_{\text{cont},i}} \quad (28)$$

Because the MAC layer protocol of IEEE802.11s draft follows EDCA, the performance of the proposed scheme is compared with EDCA and the MMDA algorithm in average throughput, average waiting time, packet drop ratio, fairness, and collision ratio in the simulation. There are three sets of results to be compared: the MMDA algorithm with DACP mechanism and ABP (called MMDA-DACP + ABP), EDCA using 5% and 30% CP ratio (called EDCA-5% and EDCA-30%), and the MMDA algorithm using 5% and 30% CP ratio of the mesh DTIM interval (called MMDA-5% and MMDA-30%), respectively, where the traffic load is varied from 0.1 to 1.0 (i.e., fully loaded at 375 kbps for each MP).

From Figures 8, 9, 10, we find EDCA has the worst performance than the other three schemes, because the source MP and the destination MP have to coordinate a channel to be used, and the source MP must contend with the

other MPs in CP. In addition, the source MP needs to reserve transmission opportunity (TXOP) by contention mechanism in DTP, which increases network overhead and more collisions. Furthermore, the TXOP cannot periodically be used in every mesh DTIM interval, so it increases the numbers of contentions and causes EDCA having worst performance. We also find that MMDA-DACP + ABP performs better than MMDA-5% and MMDA-30% in average throughput, average waiting time, and packet drop ratio when traffic load increases because MMDA-DACP + ABP allows for dynamically adjusting CP ratio and increasing DTP ratio in the mesh DTIM interval to improve wireless mesh LAN performance. Because the CP ratio of MMDA-30% is always fixed at 30%, this results in the network resources wasted and leads to the poor performance than MMDA-DACP + ABP and MMDA-5% when wireless mesh LAN is at heavy-loading situation. MMDA-5% has better performance than MMDA-30% in heavy loading, but the shortened CP of MMDA-5% is not enough for MPs to efficiently reserve MDAOPs at light loading. Therefore, in Figures 9 and 10, the average waiting time and the packet drop ratio of MMDA-5% are greater than MMDA-DACP + ABP and MMDA-30% at light loading.

Figure 11 shows the fairness comparison for these three schemes. We find that MMDA-DACP + ABP has better fairness than the MMDA algorithm because it uses adaptive backoff process and helps the MPs having less MDAOPs have higher probability to reserve MDAOPs. The adaptive backoff process also helps MMDA-DACP + ABP to reduce collision ratio as shown in Figure 12 because the adaptive backoff process divides

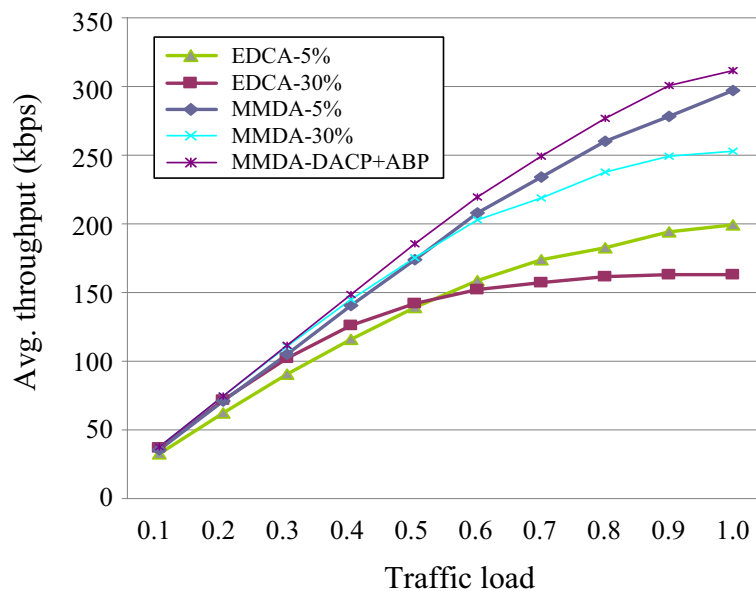
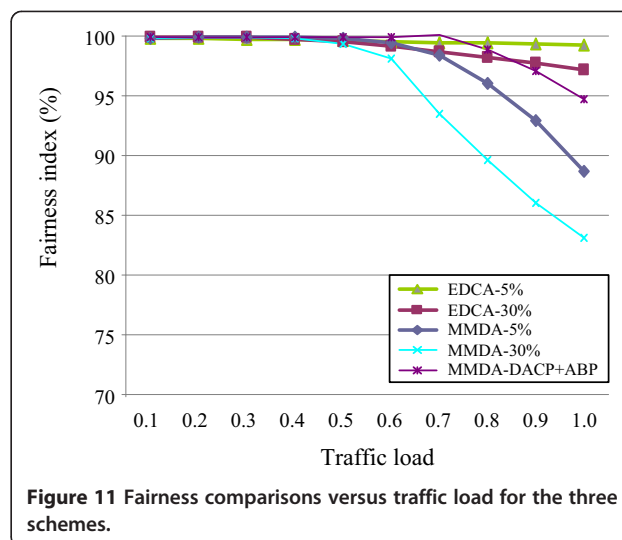
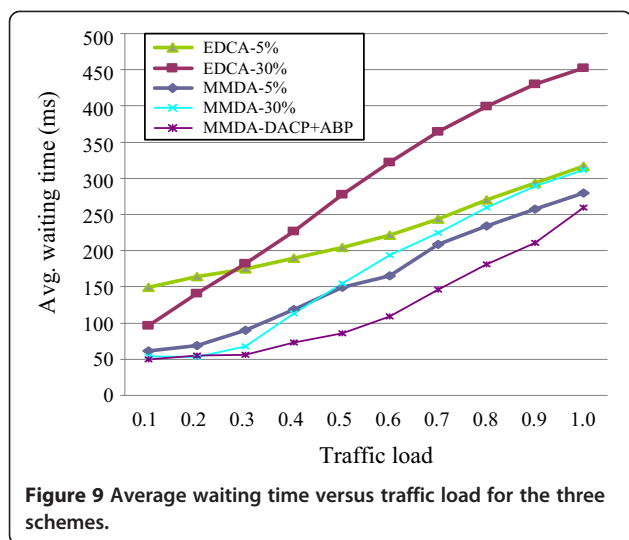


Figure 8 Average throughput versus traffic load for the three schemes.



MPs into four categories with different backoff time parameters, respectively. EDCA has the worst collision ratio because it has to contend both in CP and DTP.

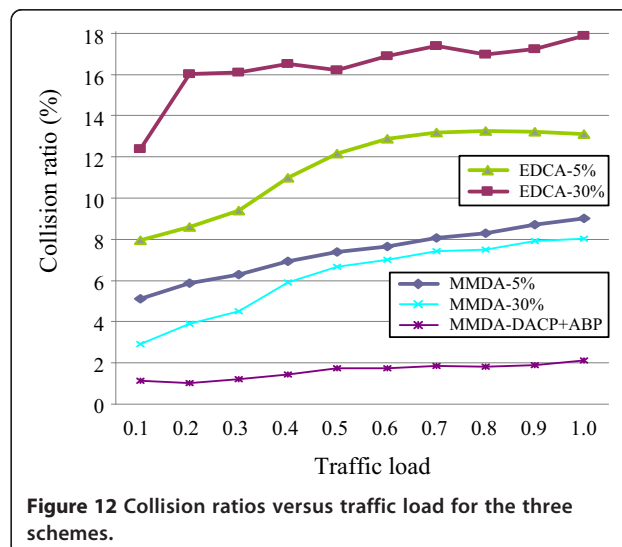
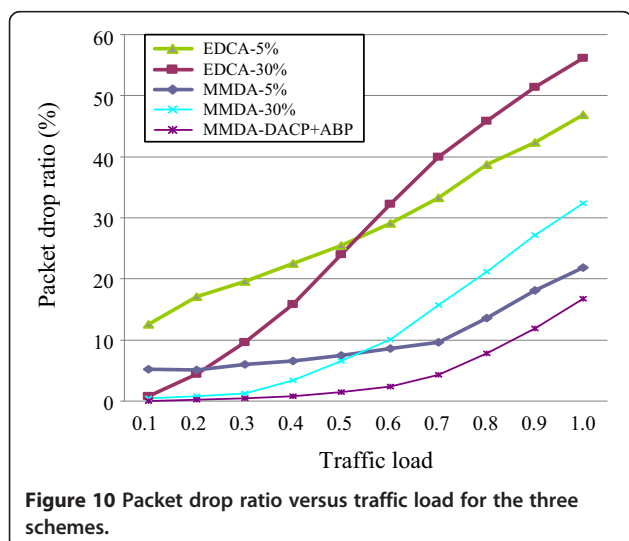
Figure 13 shows the average throughput changed by the three different MP types in MMDA-DACP + ABP. It is obvious that all MPs in wireless mesh LAN are NCP at low traffic load, and their throughput increases when traffic load increases. However, most of the NCP MPs will start DACP to change their states to ECPS because of DTP saturated when traffic load becomes heavier than 50%. As traffic load becomes heavier, the NCP MP gradually transits to ECPS, i.e., the ECPS MPs' throughput increases and the NCP MPs' throughput decreases.

In order to observe how the MPs change for the three different types using the MMDA algorithm with DACP and ABP, we set the network traffic to be fully loaded (i.e., 375 kbps for each MP) before 50 s of the simulated time and lightly loaded (i.e., 37.5 kbps for each MP) after

50 s. Figure 14 shows that the MPs start DACP to change type at the fourth second and completely transit from NCP to ECPS after 0.4 s at the fully loaded traffic, while the MPs completely transit to NCP at the 53.5 s of the simulated time at the lightly loaded traffic.

6 Conclusions

Multichannel MDA (MMDA) algorithm can make full use of multichannel environment to improve the overall performance and capacity of wireless mesh LAN, but the MMDA algorithm uses fixed contention period mechanism which causes the waste problem of network resources when wireless mesh LAN is at heavy-loading situation. Besides, the MMDA algorithm using the contention mechanism to reserve MDAOPs will cause the unfairness problem between MPs.



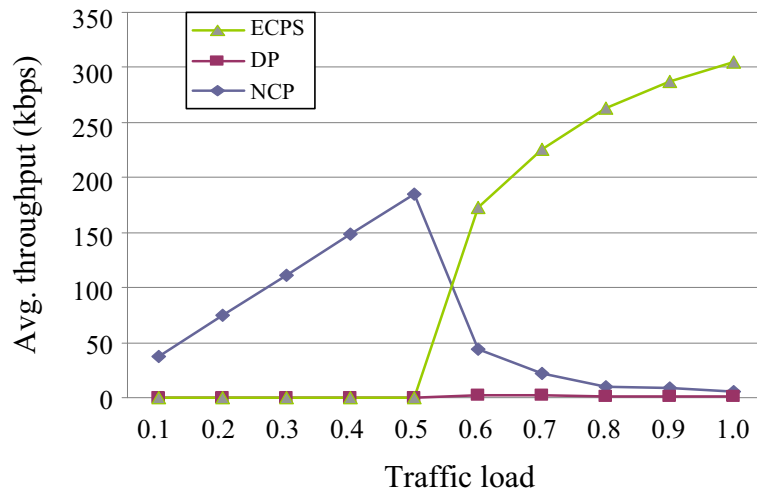


Figure 13 The average throughput versus traffic load for the three different MP types using the MMDA algorithm with DACP and ABP.

The proposed scheme uses the DACP mechanism and ABP, so it can further improve the network performance when wireless mesh LAN is at heavy-loading situation and alleviate the unfairness problem. The simulation results clearly show that in heavy-loading wireless mesh LAN environment, the MMDA algorithm using DACP mechanism and ABP outperforms the MMDA algorithm in average throughput, average waiting time, packet drop ratio, collision ratio, and fairness. The proposed scheme can truly improve the performance of the MMDA algorithm.

List of symbols

- r The evaluation parameter for ABP
- $MDAOP_{own}$ The durations of MDAOPs reserved by the MP itself
- $MDAOP_{avg}$ The durations of MDAOPs reserved by neighbor MPs
- n Total numbers of MPs in wireless mesh LAN
- W_0 The initial contention window
- p_c Collision probability caused by at least one of $n - 1$ MP transmissions
- p_t Transmission probability of each MP

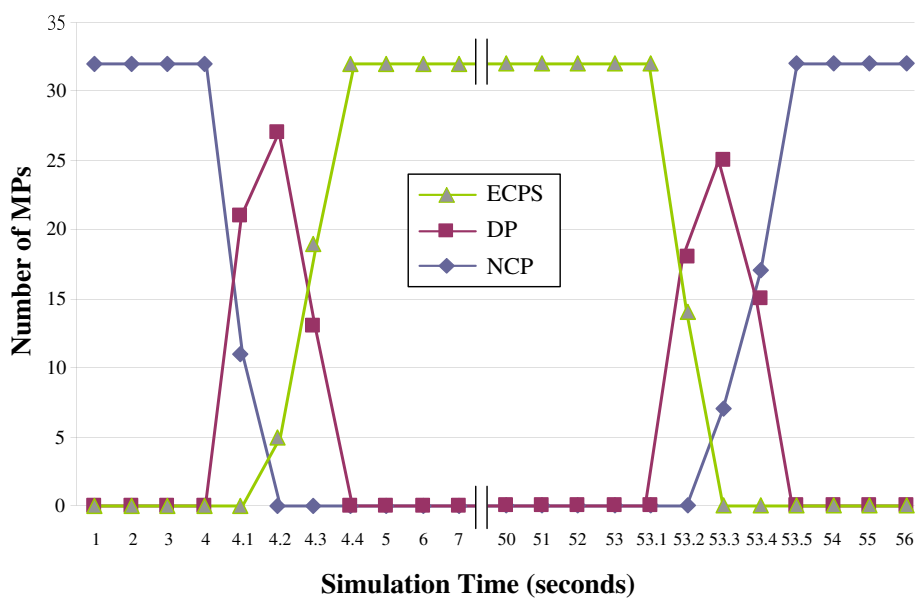


Figure 14 Number of nodes to change types versus simulation time for the three different MP types using the MMDA algorithm with DACP and ABP.

p_{succ} Probability of successful transmission
 p_i Probability of the idle channel
 p_{coll} Collision probability caused by two above MP transmissions
 T_{cp} The durations of contention period
 $T_{cp,c}$ The critical duration of CP
 I A random variable; an MP will experience i times of collision before successfully reserving a MDAOP in CP
 J A random variable; an MP will experience j empty slot times before successfully reserving a MDAOP in CP
 $P_{ss}(i, j, n)$ The joint probability mass function of the random variables I and J with n MPs
 \bar{I} The mean of I
 \bar{J} The mean of J
 T_s The duration of each successful MMDA four-way handshaking contention
 T_c The duration of each collision
 T_{MDASRQ} The duration of MDA setup request
 T_{MDASRP} The duration of MDA setup reply
 T_{MDAACK} The duration of MDA acknowledge
 T_{MDAADV} The duration of MDA advertisement
 T_{DIFS} The duration of DIFS
 T_{SIFS} The duration of SIFS
 T_r The average time to reserve an MDAOP for an MP in CP
 T_{DTIM} The duration of mesh DTIM interval
 T_{DTP} The duration of data transmission period
 T_i A slot time that should be long enough to access the channel state information
 N_a The available MDAOPs provided for MPs to reserve in DTP
 N_c The number of channels in DTP
 B The bandwidth of each channel
 D MDAOP duration
 L The average interval between two MDAOPs
 N_{min} The minimum value of n and N_a
 T_m The m th subcritical duration of CP that m MPs can successfully reserve MDAOPs
 X The original CP ratio
 Y The shortened CP ratio
 G The number of MPs that can successfully reserve MDAOPs
 S_{NCP} The average throughput of the NCP MP
 $T_{cp,s}$ The duration of shortened CP
 T_{ap} The duration of the additional period
 G_s The number of MPs that can successfully reserve MDAOPs in an additional period
 S_{ECPS} The average throughput of the ECPS MP
 Pkt_i The total transmitted packets of MP $_i$
 s Packet size
 T The total simulation time
 Tx_Pkt The total successful transmitted packets
 Tl_i The time that the i th packet leaves the queue
 Ta_i The time that the i th packet enters the queue

Pkt_g The numbers of generated packets
 Pkt_d The numbers of dropped packets
 S_i The throughput of MP $_i$
 $N_{coll,i}$ The total collision numbers of MP $_i$
 $N_{cont,i}$ The total contention numbers of MP $_i$

Abbreviations

ABP: adaptive backoff process; AC: access category; ACK: acknowledge; ADV: advertisement; AIFSN: arbitration interframe space number; AP: access point; BEB: binary exponential backoff; CA: channel assignment; CBR: constant bit rate; CLFRF: channel load first random fit; CP: contention period; CPC: contention period change; CSMA/CA: carrier sense multiple access with collision avoidance; CW: contention window; DACP: dynamic adjustable contention period; DCF: distributed coordination function; DIFS: DCF interframe space; DP: demarcation point; DTIM: delivery traffic indication message; DTP: data transmission period; ECPS: enable contention period shorten; EDCA: enhanced distributed channel access; ID: identification; LAN: local area network; MAC: medium access control; MAP: mesh access point; MCBF: multichannel best fit; MDA: mesh deterministic access; MDAOP: MDA opportunity; MIFS: MDA interframe space; MMDA: multichannel MDA; MP: mesh point; MPP: mesh point portal; NCP: normal contention period; NMST: neighbor MP status table; QoS: quality of service; SIFS: short interframe space; SMA: scheduled mesh access; SRB: semi-random backoff; STA: station; TRASS: traffic-aware switching scheme; TXOP: transmission opportunity.

Competing interests

The authors declare that they have no competing interests.

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