

eMCCA: An Enhanced Mesh Coordinated Channel Access Mechanism for IEEE 802.11s Wireless Mesh Networks

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Abstract: In this paper, we present a channel access mechanism, referred to as the enhanced mesh coordinated channel access (eMCCA) mechanism, for IEEE 802.11s-based wireless mesh networks. The current draft of IEEE 802.11s includes an optional medium access control (MAC), denoted as MCCA, which is designed to provide collision-free and guaranteed channel access during reserved periods. However, the MCCA mechanism fails to achieve the desired goal in the presence of contending non-MCCA nodes; this is because non-MCCA nodes are not aware of MCCA reservations and have equal access opportunities during reserved periods. We first present a probabilistic analysis that reveals the extent to which the performance of MCCA may be affected by contending non-MCCA nodes. We then propose eMCCA, which allows MCCA-enabled nodes to enjoy collision-free and guaranteed channel access during reserved periods by means of prioritized and preemptive access mechanisms. Finally, we evaluate the performance of eMCCA through extensive simulations under different network scenarios. The simulation results indicate that eMCCA outperforms other mechanisms in terms of success rate, network throughput, end-to-end delay, packet-loss rate, and mesh coordinated channel access opportunity-utilization.

Index Terms: IEEE 802.11s, medium access control (MAC), mesh coordinated channel access (MCCA), wireless mesh networks (WMNs).

I. INTRODUCTION

Wireless mesh networks (WMNs) have received growing attention in both the academia and the industry because they are dynamically self-organized and self-configured and have advantages such as low up-front cost, easy network maintenance, robustness and reliable service coverage [1]. These features make WMNs suitable for many applications such as broadband home networking, community and neighborhood networks, and enterprise networking. The increasing market demands have led to the development of a new standard for WMNs, referred to as IEEE 802.11s [2], which is still in the draft phase.

Fig. 1 is an example of an IEEE 802.11s-based WMN. The core components of the WMN that form its infrastructure/backbone are mesh points (MPs) that are responsible for relaying traffic, mesh access points (MAPs) that act as access points (APs) for legacy IEEE 802.11 nodes (STAs), and which

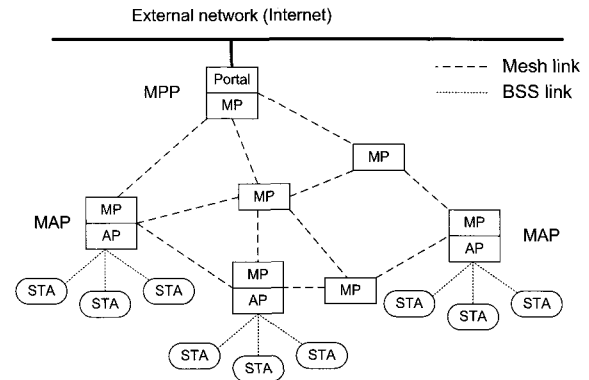


Fig. 1. Typical architecture of the IEEE 802.11s WMN.

also relaying functionalities; and a mesh point portal (MPP) or gateway node, that is connected to the Internet. Legacy STAs are attached to the MAPs and follow the principle of a generic wireless local area network (WLAN) node.

In a typical WMN, traffic from a source STA traverses multiple MPs/MAPs to reach either a destination MPP or an STA attached to another MAP within the same mesh. Such multi-hop wireless communications demand a well-designed medium access control (MAC) scheme in which radio resources are effectively accessed by contending nodes. WMNs are expected to provide quality-of-service (QoS) to meet the increasing demands of multimedia applications, such as voice and video [3], [4]. IEEE 802.11s adopts enhanced distributed channel access (EDCA) as the primary MAC for WMN; however, EDCA is a contention-based scheme and has the drawback of collisions caused by severe contention when applied to networks with high traffic volumes such as WMNs. Therefore, IEEE 802.11s also provides an optional MAC, referred to as mesh coordinated channel access (MCCA), to provide collision-free and guaranteed channel access for QoS-aware traffic during reserved periods.

With MCCA, MPs reserve some future slots, referred to as mesh coordinated channel access opportunity (MCCAOP), for collision-free and guaranteed channel access. However, the core MCCA mechanism has some drawbacks that must be addressed. The standard does not require all MPs to use MCCA. Therefore, the MPs in a WMN can be categorized into two types based on whether MCCA is activated (MCCA-enabled) or not (non-MCCA). MCCA-enabled nodes can act as owners or responders of an MCCAOP [2]. Legacy STAs do not support MCCA and therefore act as non-MCCA nodes.

The performance of the MCCA mechanism is highly affected by contention from non-MCCA nodes that are not aware of MCCAOP reservation and therefore have equal access oppor-

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tunity during reserved periods. Existing studies exploring this problem (including an earlier version of the current work [5], and [2], [6], and [7]) have agreed upon this conclusion. However, the level of MCCA performance degradation in the presence of non-MCCA nodes has not yet been analytically assessed. In this study, our probabilistic analysis of the MCCA mechanism in the presence of contending non-MCCA nodes reveals that an MCCAOP owner may not have collision-free and guaranteed access to the channel in the course of an MCCAOP. This happens because of simultaneous transmission attempts or ongoing transmissions from non-MCCA nodes that may foreshorten MCCAOPs. None of the existing mechanisms, such as [7]–[9], or [10], can ensure guaranteed access by an MCCAOP owner. The scheduled mesh access (SMA) [6] mechanism allows MCCAOP owners to continue access beyond the reserved periods in case of a delayed start caused by transmissions from non-MCCA nodes. However, this mechanism hinders the synchronization of MCCAOPs in neighboring MPs. Moreover, SMA uses the same contention parameters for MCCAOP owners and non-MCCA nodes, and therefore, it cannot ensure guaranteed access during MCCAOP. In this paper, our objective is to design a channel access mechanism that allows the owners of MCCAOPs to fully utilize their reserved MCCAOP periods.

The primary contributions of this work can be summarized as follows: (i) Through probabilistic analysis, we demonstrate that in the MCCA mechanism of IEEE 802.11s, an MCCAOP owner may not have collision-free and guaranteed access to the channel during reserved periods. (ii) We propose an enhanced mesh coordinated channel access (eMCCA) mechanism that incorporates *a) a prioritized access* mechanism to ensure that MCCAOP owners can acquire the channel when simultaneous transmission attempts are made by non-MCCA nodes, and *b) a preemptive access* mechanism that invokes early access by the MCCAOP owner if it is predicted that transmissions from non-MCCA neighbors would foreshorten the MCCAOP. (iii) We present a throughput analysis for MCCA and eMCCA mechanisms, which shows that both non-MCCA nodes and MCCAOP owners can achieve their desired throughputs in the non-reserved and reserved periods, respectively, with eMCCA mechanism. (iv) Finally, through extensive simulations, we show that our proposed eMCCA mechanism performs better than existing schemes in terms of success rate, network throughput, end-to-end delay, packet-loss rate, and MCCAOP-utilization.

The remainder of this paper is organized as follows. Section II provides a brief overview of the MCCA mechanism, describes the problem, and contains an analysis of MCCA mechanism in the presence of non-MCCA nodes. In Section III, we present a detailed design of the proposed eMCCA mechanism, and in Section IV, we derive the throughput for the MCCA and eMCCA mechanisms. In Section V, we evaluate the performance of the eMCCA mechanism. In Section VI, we review some related research. Finally, we conclude this paper in Section VII.

II. BACKGROUND AND MOTIVATION

A. A Brief Overview of the MCCA Mechanism

In this section, we briefly discuss the operation of the MCCA, which is governed by two phases. In the first phase,

an MCCAOP is set up between two adjacent MCCA-enabled MPs (namely, the MCCAOP owner and MCCAOP responder [2]). Next, in the second phase, the MCCAOP owner tries to access the channel during MCCAOP using conventional EDCA parameters. In the following section, we describe the MCCAOP reservation and access mechanism in detail.

A.1 MCCAOP Reservation

By means of the MCCA mechanism, MCCA-enabled MPs can reserve slots within a mesh delivery traffic indication message (DTIM) interval.¹ The MCCAOP owner initiates the reservation procedure by sending an MCCAOP setup request message to the intended MCCAOP responder; the message contains the offset, duration (i.e., number of slots), and periodicity. However, before sending the request, the MCCAOP owner needs to be aware of the neighborhood MCCAOP times, which include all of the MCCAOPs for which the MP or one of its neighbors is either the transmitter or the receiver. Each MCCA-enabled node must therefore broadcast an MCCAOP advertisement (MADV) message consisting of transmitter (Tx)-receiver (Rx) and an interfering times report (IR). MADV messages are generally transmitted in beacon frames. The Tx-Rx of an MP includes all MCCAOPs in which the MP is involved either as an owner or a responder, and all the times that it knows it will be busy, such as its own or its neighbors' expected beacon times. In contrast, the IR includes the MCCAOP slots in which the MP is neither an owner nor a responder, but that are reported as busy by its neighbors' Tx-Rx. Therefore, an MP can build a map of neighborhood MCCAOP times by examining both Tx-Rx and IR. The MADV message includes another important parameter, the MCCA access fraction (MAF), which is the ratio of its neighborhood MCCAOP times to the duration of the mesh DTIM interval. The maximum value of MAF that is allowed at an MP is specified as the MAF limit and is known to all MCCA-enabled MPs. At no time should the MAF of an MP exceed the MAF limit, as it is used to restrict the use of MCCA in a mesh neighborhood and allows non-MCCA nodes to have sufficient access through EDCA during the DTIM interval. After receiving the MCCAOP request message, the responder first checks whether or not the requesting slots overlap with its neighborhood MCCAOP times. The responder must also ensure that requests for MCCAOP slots do not cause its own or the MAF of its neighboring MPs to exceed their limits. If both conditions are satisfied, then the responder issues an MCCAOP setup reply message to the owner, and the MCCAOP is reserved between the owner and responder.

We illustrate the MCCAOP reservation procedure using the example in Fig. 2, in which all nodes are MCCA-enabled. Each node broadcasts the MADV message in respective beacon frames transmitted during the DTIM beacon period. The corresponding Tx-Rx and IR of each node are represented as (offset, duration) such as (4, 5), which means an MCCAOP of 5 slots in duration starting from the 4th slot of the DTIM interval. For simplicity, we have not included the periodicity field in the figure. We also assume that the periodicity is set to zero such that

¹DTIM interval is defined as the time between two consecutive mesh DTIM beacon frames and is calculated in time units (1 TU = 1024 μ s). It is the product of beacon interval and mesh DTIM period.

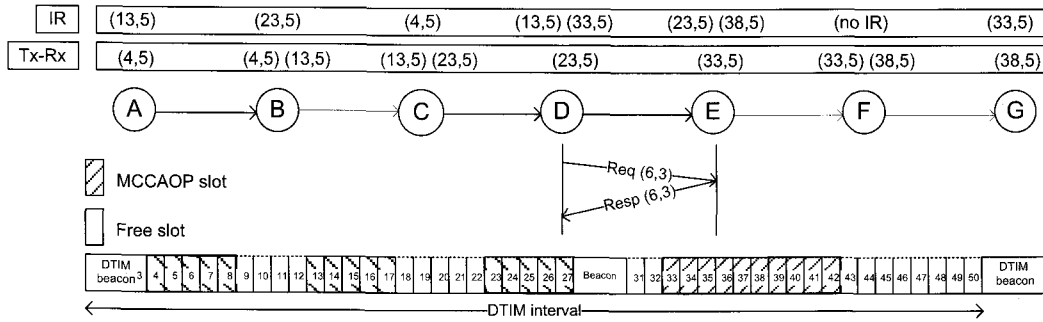


Fig. 2. MCCAOP reservation procedure.

the reservation occurs only once during the DTIM interval.

Let us consider that node D wants to set up an MCCAOP with node E. Node D first determines the slots that it cannot include in the reservation request (i.e., the neighborhood MCCAOP times of D that include (23, 5), (13, 5), (33, 5) and the IR of the receiving node E that includes (23, 5), (38, 5)). Then, node D sends an MCCAOP request (req.)—req (6, 3)—to node E. Node E confirms that (6, 3) does not overlap with its neighborhood MCCAOP times (i.e., (33, 5), (23, 5), (38, 5)). Both nodes D and E ensure that the MAF limit (we assume the value to be 0.50) is not exceeded for themselves or their neighbors for the new reservation. The new MAFs of nodes C, D, E, and F are 0.36, 0.36, 0.36, and 0.26, respectively, and none exceeds 0.50. Next, node E sends an MCCA reply message (resp)—resp (6, 3)—to node D confirming the reservation. Note that slots (6, 3) can be used simultaneously by nodes A and D, which are more than two hops away from each other. To keep the reservations active, the nodes are required to advertise Tx-Rx and IR through MADV messages at least once during the DTIMPeriodMax interval.

A.2 Access Mechanism

The MCCAOP owner needs to contend for the channel during the MCCAOP using IEEE 802.11e EDCA [11]; thus, the contention parameters are set on the basis of the access category of the MAC service data unit (MSDU). Only after successfully obtaining an EDCA transmission opportunity (TXOP) can the MCCAOP owner transmit a packet. In addition, the EDCA TXOP of the MCCAOP owner cannot extend over any MCCAOP among its neighborhood MCCAOP times.

MCCA-enabled nodes are required to maintain a reservation allocation vector (RAV) [2] for each reservation in its IR. The RAV is initialized as the duration of the corresponding reservation and activated when that MCCAOP starts. Moreover, MCCA-enabled nodes set their NAV while overhearing frames from neighboring MCCA-enabled nodes during an MCCAOP. Therefore, at no time can an MCCA-enabled node gain access to the medium if either RAV or NAV has any value other than zero. However, non-MCCA nodes can contend for the channel using the same access mechanism (i.e., EDCA) during the MCCAOP of its neighboring MPs. This allows non-MCCA nodes to affect regular MCCA operation.

Fig. 3 shows the access behaviors of different types of mesh nodes during an MCCAOP. In the figure, all four nodes, A, B,

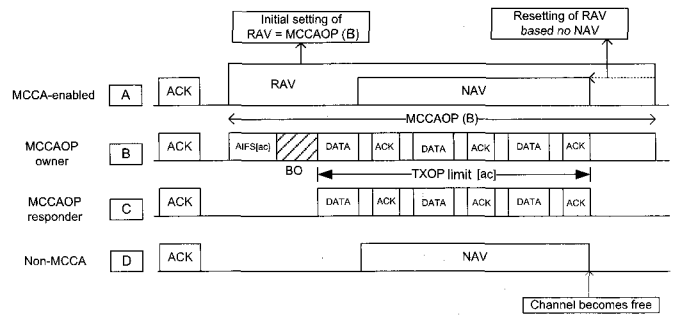


Fig. 3. Channel access during reserved MCCAOP.

C, and D, are within each others transmission range and are classified as MCCA-enabled, MCCAOP owner, MCCAOP responder, and non-MCCA, respectively. The MCCAOP owner node B must contend for the channel at the beginning of its MCCAOP. As shown in the figure, node B waits for an arbitration interframe space (AIFS) period before initiating the backoff process and can only transmit when the backoff value reaches zero; thus, node B obtains an EDCA TXOP. The only contending node at this point is the non-MCCA node D assuming this node has data to transmit. Node A first sets its RAV based on its IR, which is activated when MCCAOP (B) starts. Upon overhearing the DATA frame that node B transmits to node C, both nodes A and D set their NAV values. This also forces node A to reset its RAV until the end of node B’s TXOP.

B. Problem Description

The failure of the MCCA mechanism to provide collision-free and guaranteed channel access during MCCAOP stems from the fact that non-MCCA nodes are not aware of the reservation of MCCA-enabled nodes and are allowed respective access opportunities during the MCCAOP. The MCCAOP owner might be forced to delay access (i.e., foreshorten MCCAOP) or might not gain access to the channel at all during its reserved MCCAOP in the following cases.

- First, an MCCAOP owner might experience collisions caused by simultaneous transmission attempts from non-MCCA nodes during a reserved MCCAOP period. As illustrated in Fig. 4(a), if the MCCAOP owner and non-MCCA nodes, X and Y, simultaneously attempt to transmit after using the same backoff values and AIFSSs, then there will be a collision.

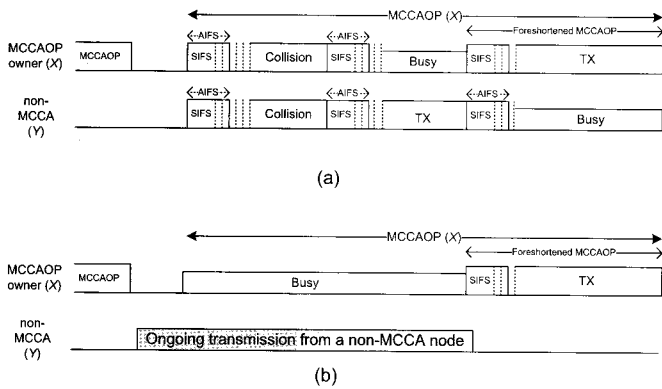


Fig. 4. (a) MCCAOP owner, X , cannot start at the beginning of its MCCAOP due to simultaneous transmission attempt from a non-MCCA node, Y and (b) MCCAOP owner, X , finds the channel as busy when its MCCAOP starts because of an ongoing transmission from the non-MCCA node, Y .

- Second, the MCCAOP can be foreshortened if a non-MCCA node wins the backoff process and obtains access to the channel during a reserved MCCAOP period. As illustrated in Fig. 4(a), if non-MCCA node, Y , wins the backoff procedure, then the MCCAOP owner, X , has to wait until it senses that the medium is idle again; only then can it initiate a transmission by successfully obtaining an EDCA TXOP.
- Third, the MCCAOP owner might not start the scheduled transmission at the beginning of its MCCAOP due to an ongoing transmission from a non-MCCA node that started before the MCCAOP. Fig. 4(b) graphically illustrates the process by which the MCCAOP owner (X) is forced to reduce its reserved period when the non-MCCA node (Y)'s transmission is initiated before the MCCAOP (X).

In all of the above cases, reserved MCCAOPs are either foreshortened or, in the worst cases, totally occupied by transmissions from non-MCCA nodes. Note that the MCCAOP owner must finish its transmission within the MCCAOP boundary. Therefore, the remaining MCCAOP slots may not be long enough for the MCCAOP owner to successfully obtain an EDCA TXOP. This problem increases the protocol overhead as the message exchange for an MCCAOP reservation becomes useless and fails to fulfill QoS requirements (i.e., delay constraints for voice and video traffic). In addition to identifying these problems, we measured the impact of contending non-MCCA nodes' transmissions on the performance of the MCCAOP owner by means of probabilistic analysis.

C. Analysis of MCCA in the Presence of Non-MCCA Nodes

It is essential to determine the probability with which an MCCAOP owner can successfully obtain a TXOP during an MCCAOP (i.e., win the contention process), in the presence of contending non-MCCA nodes. We considered a simple scenario in which the MCCAOP owner has n non-MCCA and m MCCA neighbors. To simplify the analysis, we considered a homogeneous case in which both types of nodes use the same backoff parameters. We also assumed that the nodes are always backlogged. We made the fundamental assumption that all stations attempt to transmit in a randomly chosen slot with a constant and

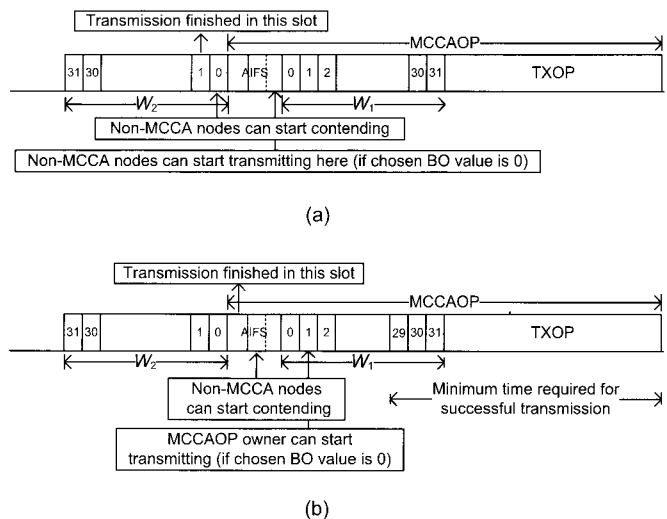


Fig. 5. Scenarios where an MCCAOP owner node needs to contend with the non-MCCA nodes for successfully obtaining a TXOP: (a) An MCCAOP owner finds the channel idle and (b) busy at the beginning of an MCCAOP.

independent probability, τ , which actually depends on collision probability, γ .

C.1 Success Probability

At the beginning of an MCCAOP, the MCCAOP owner may find the channel to be busy or idle depending on neighboring non-MCCA transmissions. Therefore, the probability that the MCCAOP owner successfully obtains a TXOP largely depends on when the immediately preceding frame transmission from a non-MCCA node ends; this process may be categorized according to the following cases.

Case 1: The immediately preceding transmission from a non-MCCA node finishes before MCCAOP, which implies that the MCCAOP owner finds the channel idle at the beginning of MCCAOP.

In this case, the non-MCCA nodes can start contending for access earlier (except when the previous transmission finishes during the last slot before MCCAOP) than the MCCAOP owner, which affects the probability that the MCCAOP owner will successfully obtain a TXOP. Let W_1 and W_2 denote the minimum contention window sizes for the MCCAOP owner and non-MCCA nodes, respectively. If the previous frame transmission ends during any of the slots in the range $(0$ to $W_2 - 1)$, then a non-MCCA node can start contending for the channel right after the last busy slot. Fig. 5(a) depicts the scenario in detail. Let us assume that the last transmission finishes during slot 1 before MCCAOP. This will allow the non-MCCA nodes to initiate the channel access procedure one slot earlier than the MCCAOP owner, and in the worst-case scenario, the non-MCCA nodes will be able to transmit before the MCCAOP owner's AIFS expires.² Therefore, even if the MCCAOP owner selects a backoff value of 0, to successfully obtain a TXOP, it needs to ensure that none of the non-MCCA nodes transmit during the last slot within AIFS or the first slot after AIFS, which yields a proba-

²For simplicity of analysis, we consider that AIFS consists of 3 slots.

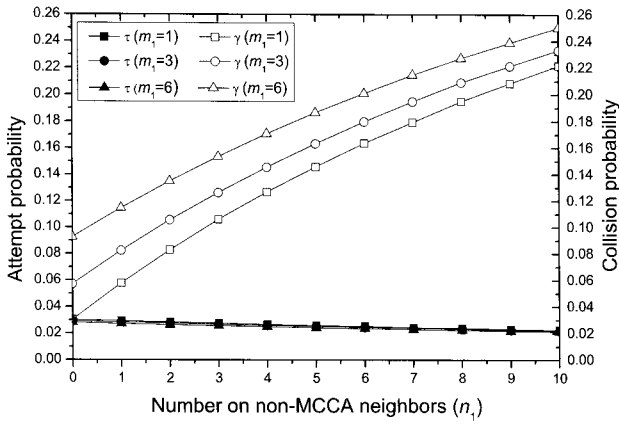


Fig. 6. Attempt probability and collision probability of a non-MCCA node for different numbers of non-MCCA and MCCA neighbors.

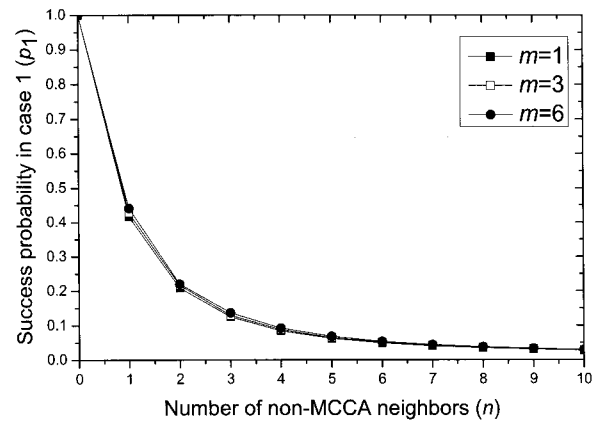


Fig. 7. Success probability of an MCCAOP owner in case 1, for different numbers of non-MCCA and MCCA neighbors.

bility of success of $1/W_2(1 - \tau)^{2n}$. Therefore, the probability that the MCCAOP owner successfully obtains a TXOP when it senses the medium to be idle during MCCAOP, denoted as p_1 , can be given by

$$p_1 = \frac{1}{W_2 W_1} \sum_{j=0}^{W_2-1} \sum_{i=1}^{W_1} (1 - \tau)^{(j+i)n}. \quad (1)$$

In (1), the value of $j = 0$ indicates a special case in which the channel becomes idle for both types of nodes right at the beginning of MCCAOP.

Case 2: The immediately preceding transmission from a non-MCCA node finishes during the MCCAOP, which implies that the MCCAOP owner finds the channel busy at the beginning of MCCAOP.

In this case, both the MCCAOP owner and the non-MCCA nodes can start contending for the channel simultaneously. Note that the MCCAOP owner requires at least (AIFS + TXOP) time to successfully access the channel (i.e., if it selects a BO value of 0) and transmit a frame. Therefore, the MCCAOP owner can successfully obtain a TXOP only when transmissions from the non-MCCA node finish before $(W_1 - \text{AIFS})$ (i.e., up to slot 28 after AIFS in Fig. 5(b)). Therefore, the MCCAOP owner can successfully obtain a TXOP if the non-MCCA node finishes during the k th slot, where k ranges from 0 to $W_2 - 1$ from the beginning of the MCCAOP. Therefore, the probability of successfully obtaining a TXOP when the MCCAOP owner node finds the medium to be busy, p_2 , can be given by

$$p_2 = \frac{1}{W_2 W_1} \sum_{k=0}^{W_2-1} \sum_{i=1}^{W_1-k} (1 - \tau)^{in}. \quad (2)$$

Note that for both cases, the numbers of eligible slots are equal (i.e., $W_1 = W_2 = 32$) and thus, both cases are equally likely to occur. Therefore, by using the *law of total probability* [12], we determine the probability (p_s) that an MCCAOP owner successfully obtains a TXOP during its reserved MCCAOP to be

$$p_s = \frac{1}{2}p_1 + \frac{1}{2}p_2. \quad (3)$$

C.2 Collision Probability

In this subsection, we derive the collision probability, γ , and attempt probability, τ , for non-MCCA nodes because both have large impacts on the probability of success of the MCCAOP owner. The collision probability of a node depends on the number of contending nodes. In the MCCA environment, a non-MCCA node can contend during both reserved and non-reserved periods. Let the number of non-MCCA and MCCA neighbors of a non-MCCA node be n_1 and m_1 , respectively. During the non-reserved period, a non-MCCA node contends with both $(n_1 + m_1)$ neighbors, while during the reserved period it contends with $(n_1 + 1)$ neighbors. Therefore, the collision probability for a non-MCCA node during the non-reserved and reserved periods, denoted as γ_1 and γ_2 , respectively, can be given by

$$\gamma_1 = 1 - (1 - \tau_1)^{n_1} (1 - \tau_2)^{m_1} \quad (4)$$

$$\gamma_2 = 1 - (1 - \tau_1)^{n_1} (1 - \tau_2) \quad (5)$$

where $(1 - \tau_1)^{n_1}$ is the probability that none of the n_1 non-MCCA neighbors transmit during a randomly selected slot and $(1 - \tau_2)^{m_1}$ is the probability that none of the m_1 MCCA neighbors transmit during a randomly selected slot. Therefore, the probability of collision γ for a non-MCCA node can be given by

$$\gamma = (1 - \alpha)\gamma_1 + \alpha\gamma_2 \quad (6)$$

where α is the value of the MAF limit that is used to limit the use of MCCA in the neighborhood of a mesh node.

Note that the collision probability is mainly determined by attempt probability τ . Kumar et al. [13] derived a general formula that relates the attempt probability to the collision probability for a given node. This formula can be represented as

$$\tau = \frac{1 + \gamma + \gamma^2 + \dots + \gamma^K}{b_0 + \gamma b_1 + \gamma^2 b_2 + \dots + \gamma^K b_K} \quad (7)$$

where b_k denotes the mean backoff duration at the k -th retransmission for a packet; $0 \leq k \leq K$. Therefore, the denominator represents the expected backoff duration while the numerator is the expected number of transmission attempts for a single packet. Based on (6) and (7), both collision and attempt probabilities can be calculated using numerical techniques.

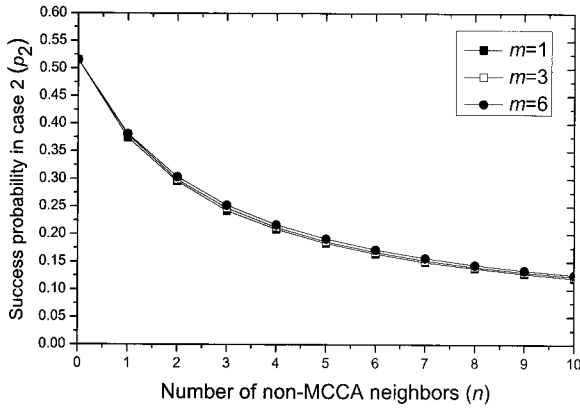


Fig. 8. Success probability of an MCCAOP owner in case 2, for different numbers of non-MCCA and MCCA neighbors.

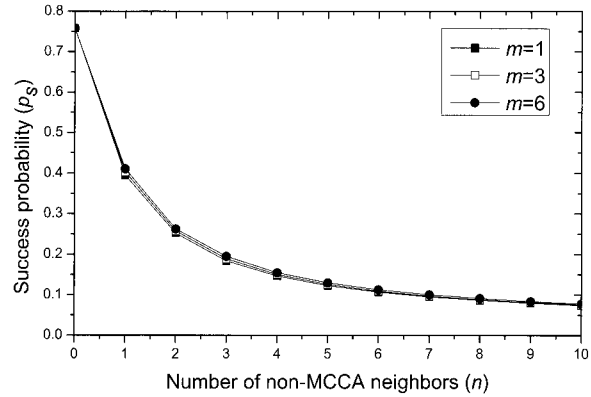


Fig. 9. Success probability of an MCCAOP owner for different numbers of non-MCCA and MCCA neighbors.

C.3 Results and Observations

In this section, we present results corresponding to the analyses described in the previous sub-sections. Fig. 6 shows the collision and attempt probabilities for non-MCCA nodes. As the number of non-MCCA neighbors (n_1) increases, the attempt probability tends to decrease slightly while the collision probability increases. Results are shown for different values of MCCA-neighbors (m_1). The probability of collision becomes higher when more MCCA neighbors are present ($m_1 = 6$). Since a non-MCCA node needs to contend with both types of nodes, the collision probability of this node is affected by the number of neighboring MCCA nodes.

The analytical results shown in Figs. 7 and 8 demonstrate the impact of contending non-MCCA neighbors on the performance of an MCCAOP owner for the cases analyzed in subsection II-C.1. Both figures graphically illustrate that increasing the number of non-MCCA neighbors decreases the probability of success for that particular MCCAOP owner. In case 1, when no contending non-MCCA neighbors are present, the probability of success is 1 because the previous transmission finishes before an MCCAOP starts. However, in case 2, the probability is only 0.52, as the MCCAOP owner finds the channel busy during MCCAOP and might not be successful in obtaining a TXOP. Note that increasing the number of MCCA neighbors does not have much of an impact on the probability of success for the MCCAOP owner. This is because MCCA-enabled nodes do not contend for the channel during a known MCCAOP and their transmissions must be finished before any other reserved MCCAOPs. Therefore, the probabilities of success in both cases depend primarily on the number of contending non-MCCA nodes. Finally, in Fig. 9, we show the overall probability of success as the number of contending non-MCCA neighbors increases.

The results of our analysis indicate that contention from non-MCCA nodes during reserved MCCAOPs bars the MCCA mechanism from achieving its desired goal (i.e., collision-free and guaranteed access to the medium during MCCAOP). In other words, if non-MCCA nodes can be restrained from accessing the channel during an MCCAOP, MCCA performance can be guaranteed. Therefore, we propose an eMCCA mechanism that effectively and efficiently prevents non-MCCA nodes

from contending with MCCA-enabled nodes in a reserved MCCAOP, thereby, ensuring collision-free and guaranteed access to the medium during the reserved MCCAOP. The eMCCA mechanism is presented in detail in the next section.

III. ENHANCED MESH COORDINATED CHANNEL ACCESS (eMCCA)

We propose the eMCCA mechanism, which works in conjunction with the MCCAOP reservation shown in subsection II.A.1. Before accessing the channel, nodes using eMCCA reserve MCCAOPs using the basic MCCAOP reservation procedure. The eMCCA mechanism comprised two parts—(a) prioritized access and (b) preemptive access, which are detailed below.

A. Prioritized Access Mechanism

Here, we present a prioritized access mechanism that prevents non-MCCA nodes from occupying the channel if they start contention with an MCCAOP owner in a reserved MCCAOP. We introduce a new inter frame space (IFS) time for the MCCAOP owner node that is defined as MCCA inter frame space (MIFS), and has a duration that is set to

$$\text{MIFS} = \text{SIFS} + \text{aSlotTime}. \quad (8)$$

Note that the duration of MIFS is equal to that of point (coordination function) inter-frame space (PIFS) used by an access point (AP) during the contention free (CF) period while operating with 802.11e hybrid coordination function (HCF) [11]. However, as there is no centralized node in a WMN, this feature cannot be used for communication between MPs. We therefore exploit this feature and set the MIFS value as shown in (8) for MCCAOP owners. At the beginning of the reserved MCCAOP, the MCCAOP owner checks to see whether the medium is idle for an MIFS period. If it senses that the medium is idle, it initiates a transmission right after the MIFS period without initiating a backoff process. The nodes that access the channel through the EDCA mechanism must wait for an AIFS period before initiating the backoff process, in which the value of AIFS is set to [11]

$$\text{AIFS} = \text{SIFS} + \text{AIFSN}[\text{AC}] \cdot \text{aSlotTime}. \quad (9)$$

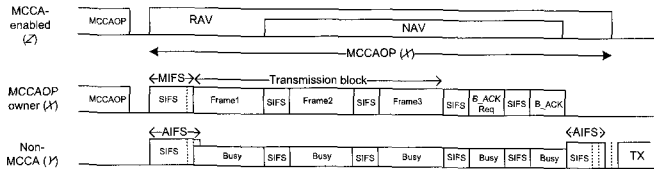


Fig. 10. Proposed prioritized access mechanism. MCCAOP owner node, X , starts transmitting after sensing the channel idle for an MIFS period.

As defined in [11], the value of the AIFS number (AIFSN) varies based on different access categories, and the value is 2 for the highest priority traffic. Therefore, all EDCA nodes must sense the channel to be idle for at least $2aSlotTime$ (i.e., equivalent to DIFS) after the SIFS period before initiating the back-off process. Therefore, if the MCCAOP owner starts transmitting after the MIFS period (i.e., only 1 slot after SIFS), all contending non-MCCA nodes will find the medium busy after their respective AIFS periods and will have to defer their transmissions. Note that even if the value of a non-MCCA node's back-off counter is zero, it will not be able to win contention, because the medium will become busy before the AIFS ends.

Fig. 10 illustrates the prioritized access mechanism in detail, with node X as the owner of MCCAOP (X), and node Y as the non-MCCA node that can contend for the channel during MCCAOP (X). Note that any other MCCA-enabled nodes (Z) within the neighborhood, must set their RAV values and therefore refrain from accessing the channel when MCCAOP (X) starts. The MCCAOP owner (X) starts transmitting after the MIFS period and thus, the non-MCCA node (Y) finds the medium busy before its AIFS expires. In this case, we assume that the value of $AIFSN = 2$ (i.e., the nodes have voice data to transmit). In the EDCA default settings [14], the AIFSN values defined for different access categories such as AC_{VO} (voice), AC_{VI} (video), AC_{BE} (best-effort), and AC_{BK} (background), are 2, 2, 3, and 7, respectively. Therefore, regardless of the type of traffic a non-MCCA node wants to transmit, the AIFS values of non-MCCA nodes will always be higher than the defined MIFS value. Thus, irrespective of the number of non-MCCA nodes and their loads, our access mechanism ensures that non-MCCA nodes refrain from transmission while the MCCAOP owner is trying to access the channel.

B. Preemptive Access Mechanism

The prioritized access mechanism presented in the previous section ensures that the MCCAOP owner can always acquire the channel even when non-MCCA nodes try to contend simultaneously. However, the MCCAOP owner must wait if it finds the channel to be busy when MCCAOP starts. This might happen if a non-MCCA node occupies the channel before the MCCAOP and the transmission carries over into the MCCAOP slots. The MCCAOP owner is therefore forced to foreshorten the MCCAOP, and in the worst case scenario, the MCCAOP owner may fail to obtain an EDCA TXOP during the reserved MCCAOP. This situation results not only in under-utilization of the MCCAOP but also increases protocol overhead due to useless handshaking to obtain an MCCAOP reservation. Furthermore, if MCCAOP owners cannot utilize their reserved MCCAOP peri-

ods, it may not be possible to ensure QoS. We therefore propose a preemptive access mechanism that restrains non-MCCA nodes from attempting transmissions that might foreshorten a reserved MCCAOP. The following sub-sections describe the mechanism in detail.

B.1 Basic Idea

When the channel becomes idle after the transmission of a non-MCCA node, the next MCCAOP owner preempts and accesses the channel early if the estimated channel occupancy time for the next non-MCCA transmission is greater than the preemption time. The preemption time is defined as the interval between the end of the immediately preceding transmission from a non-MCCA node and the start of the next MCCAOP. Note that if the estimated channel occupancy time (which depends on the type of traffic and current channel conditions) of the next non-MCCA transmission is greater than the preemption time, the reserved MCCAOP will be foreshortened and the MCCAOP owner may not be able to successfully access the channel. Therefore, the MCCAOP owner invokes preemptive access and occupies the channel using the MIFS setting right after the non-MCCA transmission immediately preceding it finishes. In contrast, if the estimated channel occupancy time is not greater than the preemption time, the next transmission is more likely to be finished before the MCCAOP and will not foreshorten the MCCAOP. Therefore, the MCCAOP owner waits until the end of the next non-MCCA transmission.

Using the preemptive mechanism, the MCCAOP owner actually accesses the channel before its scheduled MCCAOP starting time. Therefore, any non-MCCA node that would have transmitted during that period before MCCAOP, will now need to access the channel after the MCCAOP owner finishes its transmission. However, the overall performance gain of the eMCCA outweighs the increased waiting time imposed on a few non-MCCA nodes. Furthermore, the use of preemptive access does not affect the synchronization of other MCCAOP reservations as it does not stretch the MCCAOP boundaries and is initiated early only when feasible. Moreover, preemptive access retains the original reservation information and does not advertise any new MADV messages.

The effectiveness of the preemptive access mechanism depends largely on estimations of the channel occupancy time for the type of packet that will be transmitted next by the non-MCCA neighbor of an MCCAOP owner. After ascertaining the packet type to be transmitted next, along with its expected channel occupancy time, a preemption condition can also be set.

B.2 Estimation of the Expected Channel Occupancy Time

In previous work [5], we assumed that all packets in the network were of the same size and had equal average transmission times. However, these assumptions may sometimes result in mistaken preemption. In practice, heterogeneous traffic (i.e., voice, video, web, FTP) is likely to exist in a WMN and packet sizes will differ. Although each type of traffic generates packets of a fixed size, their channel occupancies or channel busy times will vary based on current channel status. For example, even if the packet size is small, it may occupy the channel for a long time if the current channel condition is poor (i.e., uses

a low data rate). Therefore, preemptive access would be more efficient if we consider channel occupancy times for individual packet types.

We consider that l different types of packets exist in the WMN corresponding to l different types of traffic. Apart from these legitimate packet types, packets that have been involved in collisions are also likely to exist. We designate such packets as $(l + 1)$. The MCCAOP owner uses an exponentially weighted moving average (EWMA) to estimate the value of the expected channel occupancy time for a packet of type i , $E[t_i]$, using

$$E[t_i] = \beta t_i + (1 - \beta)E[t_i] \text{ where } 1 \leq i \leq l + 1 \quad (10)$$

where t_i is the channel occupancy time for the i th type packet under current channel conditions and β is a tuning parameter used to smooth the estimated value. Through extensive simulations, we set the value of $\beta = 0.12$, because this value produces the best estimations of long term average channel occupancy time.

B.3 Estimation of the Next Packet Type

The MCCAOP owners observe prior transmissions from non-MCCA nodes in their neighborhood in order to estimate the packet type of the next non-MCCA transmission that might occupy the channel when the medium becomes idle after the end of the immediately preceding non-MCCA transmission. Note that a non-MCCA node performs its normal operation and is not required to estimate the type of the packet that it might transmit next; rather, the next MCCAOP owner should estimate this through observations. By overhearing and decoding the packet size in an individual transmission, the MCCAOP owner can determine the type of packet that was transmitted in its non-MCCA neighborhood. The next challenge is to estimate the subsequent packet type. During the preemption time, a legitimate transmission might occupy the channel, or a collision might occur. The prediction of collisions is uncertain, as it is not possible to determine the exact type of packets that will collide. If the MCCAOP owner cannot decode the received packet correctly, the owner identifies it as one that has collided. Currently, our data in such situations are limited to prior observations. The Dempster-Shafer (DS) theory of evidence [15] has proved to be a useful tool for making predictions using such imprecise and uncertain data. Using the DS theory of evidence, we determine the mass or basic probability assignment (bpa) for each type of packet. To determine the mass or bpa, we consider evidence from two sources, based on observations of prior packet types. The masses are then combined using the DS rule of combination, and the estimation that yields the maximum joint-mass is selected as the next packet type.

The first step when using the DS theory of evidence is to identify the frame of discernment (Θ), which is an exhaustive set of mutually exclusive events. Depending on the evidence, a mass function m can be assigned to subsets $A_i \subseteq A$ of the power set $A = 2^\theta$, such that the mass of the null subset $m(\phi)$ is zero, and the sum of the masses $m(A_i)$ for given evidence is 1; this yields [15]

$$m(A_i) \rightarrow [0, 1]; \quad m(\phi) = 0; \quad \sum_{A_i \subseteq A} m(A_i) = 1. \quad (11)$$

In our case, there are $(l + 1)$ possible events (i.e., assuming l legitimate packet types and one additional type for collided packets, represented as $(l + 1)$ th type). Therefore, our frame of discernment is, $\Theta = A_1, A_2, \dots, A_{l+1}$ where A_i ; $1 \leq i \leq l + 1$, represents a packet of type i .

We define the first mass function, $m_1(A_i)$, by observing the preceding N transmissions from the non-MCCA nodes. It is given by

$$m_1(A_i) = \begin{cases} \frac{C(A_i)}{N}, & i = 1, 2, \dots, l \\ 1 - \sum_{i=1}^l \frac{C(A_i)}{N}, & i = l + 1 \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

where $C(A_i)$ is the frequency of occurrence for A_i during the N observations.

Our second line of evidence is derived from the fact that the sequence of prior packet types has an impact on the probability of occurrence of the next packet. In other words, if a number of consecutive transmissions are found to be of the same type, then it is more likely that the next packet might be of a different type. We observe the preceding $(r - 1)$ transmissions and determine the mass on the type of r th packet. Therefore, our second mass function, $m_2(A_i)$, is defined as

$$m_2(A_i) = \begin{cases} \prod_{k=1}^r I_i^k, & i = 1, 2, \dots, l + 1 \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

where $I_i^k = P_{A_i}$ is the probability of occurrence of A_i in the k th observation or $I_i^k = 1 - P_{A_i}$ is the probability that A_i has not occurred during the k th observation. Note that from the first line of evidence, we are able to obtain the long run probabilities for the occurrences of different values of A_i and we use that to determine P_{A_i} .

On obtaining the individual masses from the two observations, using the DS rule of combination, we can measure the joint-mass, m_{1-2} , for the two mass functions m_1 and m_2 , using the following equation [16]:

$$m_{1-2}(A_i) = \frac{\sum_{A_p \cap A_q = A_i} m_1(A_p)m_2(A_q)}{1 - K} \quad (14)$$

when $A_i \neq \phi$; and $m_{1-2}(\phi) = 0$, and where $K = \sum_{A_p \cap A_q = \phi} m_1(A_p)m_2(A_q)$ is a measure of the degree of conflict between the two masses.

Finally, we assume the *next_packet_type* to be the one for which the value of joint-mass is maximum and that it can be found by

$$\text{next_packet_type} = \arg \max_{A_i \in \Theta} m_{1-2}(A_i). \quad (15)$$

B.4 Setting the Preemption Condition

After obtaining the joint-mass from (15), the owner of the next MCCAOP may perceive that the i th (where $1 \leq i \leq l + 1$) type packet will most likely be transmitted by a non-MCCA neighbor. The owner measures the $E[t_i]$ and compares the resulting value with the preemption time, t_{pmt} . Note that if $E[t_i]$

exceeds t_{pmt} , it is more likely that the transmission of the i th type packet would extend into the MCCAOP slots and the slots already reserved by the MCCAOP owner will be foreshortened. Therefore, the MCCAOP owner preempts and acquires the channel right after the last busy period. In contrast, if $E[t_i]$ does not exceed t_{pmt} , then the probable transmission from a non-MCCA node is more likely to be finished before MCCAOP. In this case, the MCCAOP owner waits until the next transmission finishes and again compares the new values of $E[t_i]$ and t_{pmt} . Therefore, the preemption condition for an MCCAOP owner can be defined as

- 1: **if** ($E[t_i] > t_{\text{pmt}}$) **then**
- 2: *preempt and acquire the channel early*
- 3: **else**
- 4: *wait until the end of next transmission and goto step 1*
- 5: **end if**

B.5 An Example

We consider the simple scenario as depicted in Fig. 11, in order to illustrate the preemptive access mechanism. The MCCAOP owner detects that the channel becomes idle at time t' and measures the t_{pmt} period. Using the DS theory of evidence, the user also learns that the next probable packet type is i . It then measures the $E[t_i]$ using (10). As shown in Fig. 11(a), $E[t_i]$ exceeds t_{pmt} and MCCAOP is foreshortened by t_{delay} period. Therefore, the MCCAOP owner invokes preemptive access and acquires the channel at time t' (as shown in Fig. 11(b)) using the proposed prioritized access mechanism. The user then starts to transmit its queued frames. Non-MCCA nodes can access the channel after the MCCAOP owner node finishes its transmission at t'' . Note that the Tx-Rx and IR of other MPs will not be affected as the preempting node does not advertise any new Tx-Rx or IR. It keeps the original MCCAOP reservation and preempts in the non-MCCAOP periods only.

C. Acknowledgment Policy

A general requirement of wireless channel access mechanisms (i.e., DCF, EDCA, MCCA) is that every frame needs to be acknowledged by the receiver with an acknowledgment (ACK) frame. This imposes extra overhead and reduces channel efficiency as MAC and PHY overhead are major causes of system inefficiency [17]. As a result, in an effort to further increase channel usage efficiency, we included the immediate block ACK [11] policy in our scheme.

In our proposed eMCCA mechanism, adjacent non-MCCA nodes cannot access the channel while the MCCAOP owner is transmitting. As a result, there are no frame losses due to collisions caused by simultaneous transmission from non-MCCA neighbors, or transmissions from hidden nodes,³ and only a noisy channel can cause frame loss. Therefore, channel efficiency can be increased if the MCCAOP owner transmits the block of data frames with SIFS intervals between consecutive frames. As shown in Fig. 10, after transmitting the block of frames, it requests a block acknowledgment ($B_{\text{ACK}}Req$) from the receiver. After obtaining the B_{ACK} frame from the receiver,

³MCCA reservation implicitly assumes that nodes outside the two-hop neighborhood of a link do not interfere with the MCCAOP on that link.

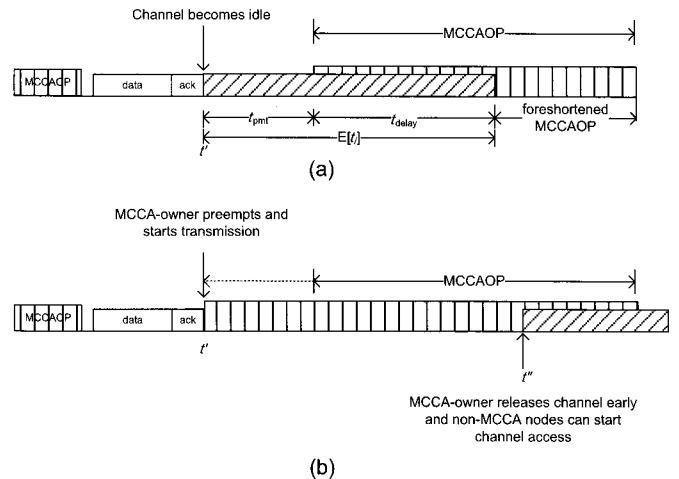


Fig. 11. (a) MCCAOP might be foreshortened by t_{delay} period if an i th type packet is transmitted when the channel becomes idle at t' and (b) MCCAOP owner preempts and starts its transmission at t' and releases the channel early at t'' .

the owner receives confirmation about the frames that have been transmitted successfully. If there are frames that are not acknowledged in the B_{ACK} frame, the owner can resend them within the same MCCAOP (or during the next reserved MCCAOP) either individually or in another block.

IV. THROUGHPUT ANALYSIS

In this section, we derive the throughput for the MCCA and eMCCA mechanisms. Our throughput analysis reveals that the eMCCA mechanism prevents non-MCCA nodes from gaining undesired throughput in the reserve period; and, at the same time it ensures that both the MCCAOP owners and the non-MCCA nodes achieve their desired throughputs in the reserved and non-reserved periods, respectively. For simplicity of analysis, we consider that both MCCAOP owners and non-MCCA nodes are saturated and transmit packets of a single access category.

A. MCCA Throughput

We consider a mesh neighborhood consisting of n non-MCCA and m MCCAOP owner nodes. Let N be the number of transmission slots in a DTIM interval, and t_s be the length of a transmission slot. A transmission slot is defined as the medium occupancy time during a transmission attempt. Therefore, the average length of a transmission slot is given by

$$E[t_s] = t_{\text{AIFS}} + E[\text{BO}] \cdot \delta + t_{\text{DATA}} + t_{\text{SIFS}} + t_{\text{ACK}} \quad (16)$$

where $E[\text{BO}]$ is the expected number of idle slots (i.e., generic slots [11]) to get the first busy slot, δ is the duration of a generic slot, t_{DATA} and t_{ACK} are the transmission time of the DATA and ACK frames, respectively. The packet size and data rates are assumed to be constant. The value of $E[\text{BO}]$ can be found using $E[\text{BO}] = 1/p_{tr} - 1$, where p_{tr} is the probability that there is atleast one transmission in the considered slot time. Therefore, we have, $N = t_{\text{DTIM}}/E[t_s]$, where t_{DTIM} the duration of

the DTIM interval excluding the time required for MCCAOP reservation.⁴

Let N_r and N_{nr} be the number of transmission slots in the reserved (i.e., MCCAOP times) and non-reserved periods during t_{DTIM} , which is controlled by the value of MAF limit, α , and can be defined as $N_r = N\alpha$ and $N_{nr} = N(1 - \alpha)$. In line with [18], we derive the probability of successful transmission by a non-MCCA node, p_s^{nc} , using

$$p_s^{nc} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \quad (17)$$

The number of successful transmissions by a non-MCCA node in the non-reserved periods, N_s^{nc} , follows a binomial distribution with parameters (N_{nr}, p_s^{nc}) . As a result, we have, $E[N_s^{nc}] = N_{nr}p_s^{nc}$. Therefore, the average throughput for a non-MCCA node in the non-reserved period, denoted as Φ_{nc} , is given by

$$\Phi_{nc} = \frac{E[N_s^{nc}]L}{t_{\text{DTIM}}n} \quad (18)$$

where L is the size of a data frame.

In the reserved periods, non-MCCA nodes contend with an MCCAOP owner. However, non-MCCA nodes might start the contention before the MCCAOP owner (see subsection II-C for details). To keep the analysis simple, we assume that the number of contending nodes is $(n+1)$ (i.e., n non-MCCA nodes and the MCCAOP owner), and each node transmits in a randomly selected slot with probability, τ .⁵ Therefore, the probability that an MCCAOP owner or a non-MCCA node successfully transmits in the reserved period, p'_s , can be given by

$$p'_s = \frac{(n+1)\tau(1-\tau)^n}{1-(1-\tau)^{n+1}}. \quad (19)$$

In contrast, the probability that an MCCAOP owner successfully transmits in a reserved slot, p_s , is given in (3). Therefore, the probability that a non-MCCA node successfully transmits in the reserve period is given by, $p'_s = p'_s - p_s$. Thus, we can determine the average number of successful transmission by a non-MCCA node in the reserved period as, $E[N_s^{ncr}] = N_r p'_s$. Therefore, the average throughput achievable by a non-MCCA node during the reserved period, Φ_{ncr} , is given by

$$\Phi_{ncr} = \frac{E[N_s^{ncr}]L}{t_{\text{DTIM}}n}. \quad (20)$$

The number of successful transmissions by an MCCAOP owner in the reserved periods, N_s^{mc} , follows a binomial distribution with parameters (N_r, p_s) , therefore, we have $E[N_s^{mc}] = N_r p_s$. Thus, average throughput achieved by an MCCAOP owner in the reserved period, Φ_{mc} , is given by

$$\Phi_{mc} = \frac{E[N_s^{mc}]L}{t_{\text{DTIM}}m}. \quad (21)$$

By combining (18), (20), and (21), we derive the aggregate throughput for MCCA mechanism, Φ , as

$$\Phi = \frac{(E[N_s^{nc}] + E[N_s^{ncr}] + E[N_s^{mc}]L)}{t_{\text{DTIM}}}. \quad (22)$$

⁴Note that both MCCA and eMCCA mechanisms have same overhead for MCCAOP reservation.

⁵For simplicity, we consider that both MCCA and non-MCCA nodes make attempt with the same probability, though in reality, it might vary.

B. eMCCA Throughput

Let t'_s be the duration of a transmission slot for MCCAOP owner transmissions. Let N'_r and N'_{nr} be the number of transmission slots in the reserved and non-reserved periods, respectively, during the DTIM interval, t_{DTIM} , with an MAF limit α . Thus, in eMCCA, we have $N'_r = N\alpha$ and $N'_{nr} = (t_{\text{DTIM}} - N'_r t'_s)/E[t_s]$.

In eMCCA, a node transmits after sensing that the channel is idle for an MIFS period without invoking a backoff process. In the analysis, we consider that a node transmits a single packet during an EDCA TXOP and thus, uses the regular ACK policy. Therefore, we have

$$t'_s = t_{\text{MIFS}} + t_{\text{DATA}} + t_{\text{SIFS}} + t_{\text{ACK}} \quad (23)$$

where t_{MIFS} is the MIFS duration.

Using eMCCA, an MCCAOP owner can have guaranteed access in the reserved period without risk of collisions. As a result, the number of successful transmissions by an MCCAOP is N'_r . The average throughput achievable by an MCCAOP owner, denoted Ψ_{mc} , can be given by

$$\Psi_{mc} = \frac{N'_r L}{t_{\text{DTIM}}m}. \quad (24)$$

In contrast, the average number of successful transmissions by non-MCCA nodes in N'_{nr} transmission slots is $N'_{nr} p_s^{nc}$, where p_s^{nc} can be obtained from (17). Therefore, the average throughput achievable by a non-MCCA node, denoted as Ψ_{nc} , can be given by

$$\Psi_{nc} = \frac{(N'_{nr} p_s^{nc})L}{t_{\text{DTIM}}n}. \quad (25)$$

Finally, combining (24) and (25), we derive the aggregate throughput for the eMCCA mechanism, Ψ , as

$$\Psi = \frac{(N'_r + N'_{nr} p_s^{nc})L}{t_{\text{DTIM}}}. \quad (26)$$

C. Analytical and Simulation Results

Figs. 12 and 13 depict the analytical results as well as the results obtained from simulations. We assumed that each MP is backlogged and sends packets of the same size (i.e., 160 bytes) and considered the data rate to be 56 Mbps. We also assumed that the number of MCCAOP owners was the same as that of non-MCCA nodes (i.e., $m = n = 5$). General simulation parameters are shown in Table 1. The MAF limit, α is set to 0.5 which determines that MCCAOP owners and non-MCCA nodes should have equal time available to access the channel. However, as shown in the Fig. 12 (both in the analysis and simulation results), non-MCCA nodes achieve much higher throughput (i.e., both in the reserve and non-reserve periods) with MCCA mechanism. This is because of the fact that, MCCA mechanism allows non-MCCA nodes to contend in the reserved periods. When this happens, in the reserved period, an MCCAOP owner needs to contend with 5 non-MCCA nodes; as a result, MCCAOP owners do not achieve their desired throughput. Fig. 13 shows the unfairness inherent in achieving average throughput by an MCCAOP owner and a non-MCCA with MCCA mechanism.

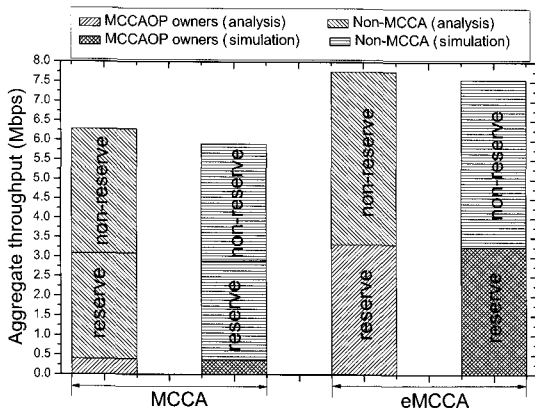


Fig. 12. Aggregate throughput achieved by MCCAOP owners and non-MCCA nodes in the reserved and non-reserved periods with MCCA and eMCCA mechanisms.

In contrast, eMCCA ensures that non-MCCA nodes achieve their desired throughput (i.e., achieved by utilizing the non-reserve period only) without affecting MCCAOP owners transmissions. As a result, MCCAOP owners using the proposed eMCCA mechanism achieve much higher throughput than that of the MCCA mechanism. Moreover, because of MIFS settings and no backoff policy by the MCCAOP owners, there remains unused reserve periods where non-MCCA nodes can transmit. Therefore, non-MCCA nodes achieve more throughput than they would have been able to achieve in the non-reserve period with the MCCA mechanism.

We observed (from the throughput analysis and performance results presented in this section) that the proposed eMCCA (i.e., prioritized and preemptive access) effectively eliminates unfair channel acquisition by non-MCCA nodes in the reserve period. Thus, eMCCA allows MCCAOP owners to efficiently utilize their allocated time share (i.e., reserve period) while still allowing non-MCCA nodes achieve their desired throughput by utilizing the non-reserve period.

V. PERFORMANCE EVALUATION

A. Simulation Environments

We evaluated the performance of the proposed scheme by way of extensive simulations using ns-2 [19]. We utilized an exemplary mesh network consisting of 49 stationary mesh nodes that were placed in a (7×7) grid over an area of $350 \text{ m} \times 350 \text{ m}$. We used both intra-mesh flows and flows that had an end-point outside of the WMN (i.e., inter-mesh flows). The sources of the flows were randomly chosen for both intra- and inter-mesh flows, whereas the destination(s) was the MPP for inter-mesh flows and randomly chosen MAPs for intra-mesh flows. We used hybrid wireless mesh protocol (HWMP) [2] (i.e., the default routing protocol for IEEE 802.11s WMNs) and expected forwarding time (EFT) [20], as the routing protocol and metric, respectively.

Three types of traffic (voice, video, and DATA) were considered to be present in the network. For voice traffic, we chose the G.711 codec as it is a popular and widely deployed codec. The voice packet size was assumed to be 160 byte with a packet

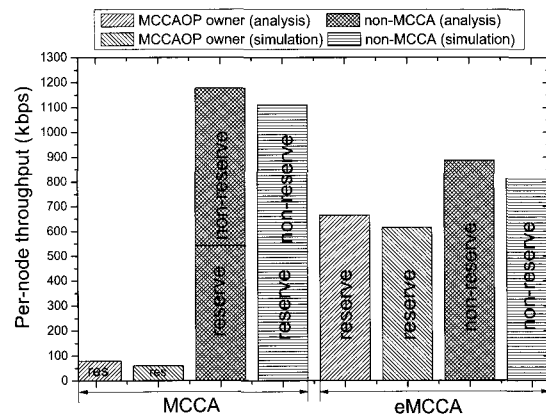


Fig. 13. Per-node throughput achieved by an MCCAOP owner and a non-MCCA node in the reserved and non-reserved periods with MCCA and eMCCA mechanisms.

Table 1. System parameters used in simulation.

| Parameter | Value |
|--------------------|------------------|
| Mesh DTIM interval | 400 ms |
| MCCA slot duration | $32 \mu\text{s}$ |
| MAF limit | 0.50 |
| SIFS | $16 \mu\text{s}$ |
| MIFS | $25 \mu\text{s}$ |
| AIFS[voice] | $34 \mu\text{s}$ |
| AIFS[video] | $34 \mu\text{s}$ |
| AIFS[data] | $43 \mu\text{s}$ |
| PHY preamble | $20 \mu\text{s}$ |
| Basic rate | 6 Mbps |

inter-arrival time of 20 ms. We used H.263 codec to generate video traffic, with a payload of 512 bytes. Both voice and video traffic are extremely delay sensitive; the maximum tolerable delays for voice and video traffic are 60 ms and 100 ms, respectively. We used real-time transport protocol (RTP) on top of UDP to deliver the real-time traffic. Node IDs were set when they were selected. Voice and video flows were associated with nodes with odd and even IDs, respectively. We assumed that every selected node generated data traffic at a constant bit rate (4 packets/sec) and assumed that the packet size to be 1024 bytes. Table 1 summarizes the system parameters we used in the simulations.

All nodes were equipped with an 802.11a radio and configured to communicate over the same channel in the 5 GHz band. The auto rate fallback (ARF) [21] mechanism was implemented in each node so that the best possible rate is selected for a particular transmission. However, control packets (i.e., MADV, reservation request, and response) used the basic rate.

The evaluation results for two different scenarios will be discussed in the subsequent sections. In the first scenario, we show how the presence of non-MCCA nodes affects the performance of MCCA-enabled nodes. In the second scenario, we show the impact of network size on the overall network performance. Each simulation run was repeated 15 times, and averaged results were plotted.

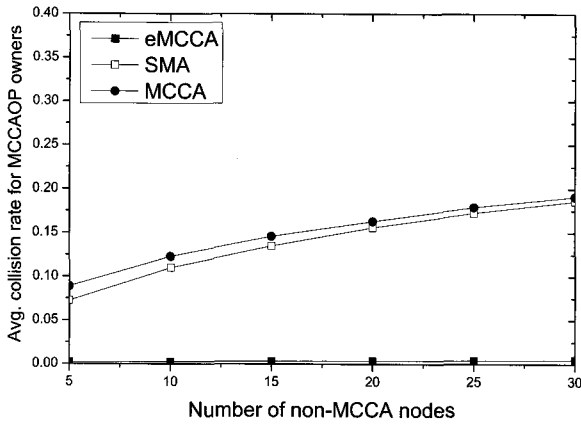


Fig. 14. Average collision rate for MCCAOP owners as the number of non-MCCA nodes is increased.

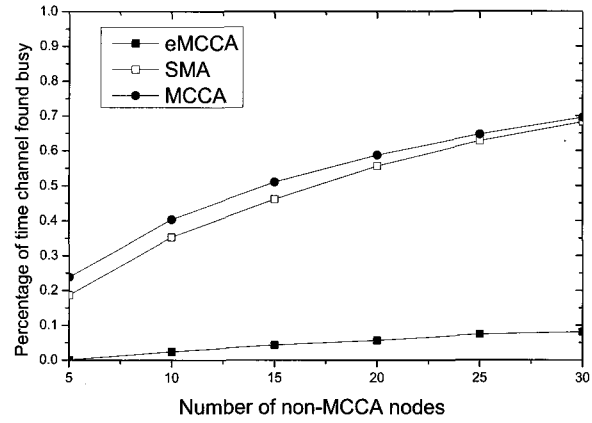


Fig. 15. Percentage of time channel is found busy by MCCAOP owner nodes.

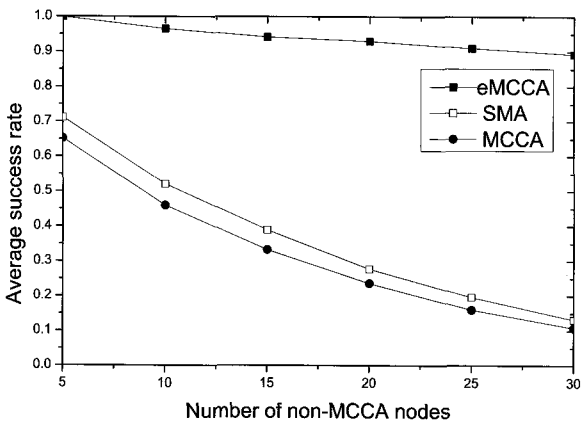


Fig. 16. Average Success rate for MCCAOP owner nodes with increasing number of non-MCCA nodes.

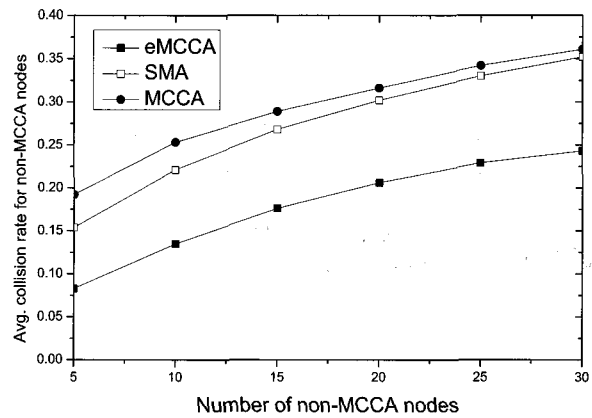


Fig. 17. Average collision rate experienced by non-MCCA nodes as the number of non-MCCA nodes is increased.

B. Scenario 1

First, we evaluated the impact of non-MCCA nodes on the performance of MCCA-enabled nodes for eMCCA, SMA, and MCCA mechanisms. We devised a scenario in which 19 MCCA-enabled nodes were randomly selected from the grid, and we gradually increased the number of non-MCCA nodes from 5 to 30 in order to measure the following performance metrics: (i) Average collision rate of the MCCAOP owner nodes; (ii) percentage of time during which the MCCAOP owner node finds the channel busy and cannot initiate a transmission; (iii) average success rate of MCCAOP owners within the reserved MCCAOP period; and (iv) average collision rate for non-MCCA nodes.

In Fig. 14, we show the average collision rate experienced by MCCAOP owners in the presence of contention from non-MCCA nodes. As we increased the number of non-MCCA nodes, the collision rate increased when MCCA and SMA were utilized. This is because non-MCCA nodes could simultaneously contend with their MCCA counterparts for the channel, with collisions occurring when their backoff values expired at the same time. In contrast, when eMCCA was utilized, the MCCAOP owner did not perform a backoff, and the user occupied the channel after finding that it was idle for the MIFS period. As a result, collisions caused by simultaneous transmissions from

non-MCCA nodes did not occur. In addition, by preempting channel access, the MCCAOP owner could avoid collisions that may have occurred if non-MCCA nodes had been contending before MCCAOP. Therefore, both the MIFS setting and preemptive channel access allow eMCCA to avoid collisions caused by non-MCCA node transmissions.

Another interesting observation is graphically depicted in Fig. 15. The figure shows the percentage of time that MCCAOP owners find the channel busy, thereby resulting in failure to initiate transmissions during MCCAOP. As the number of non-MCCA nodes increases, the probability that a non-MCCA node will transmit just before MCCAOP increases. Therefore, the MCCAOP owner often finds the channel busy with MCCA and SMA mechanisms, and fails to initiate a transmission during its MCCAOP. However, when with eMCCA is used, non-MCCA transmissions (that might foreshorten an MCCAOP) are effectively preempted and thus, MCCAOP owners rarely find the channel busy during their MCCAOPs.

Fig. 16 shows the average success rates achieved by MCCAOP owners as we increased the number of non-MCCA nodes. With eMCCA, we could ensure that the MCCAOP owner won contention when simultaneous transmission attempts were made. In addition, the preemption mechanism did not allow MCCAOPs to be reduced due to transmissions from non-MCCA nodes. Therefore, success rates for eMCCA did not significantly

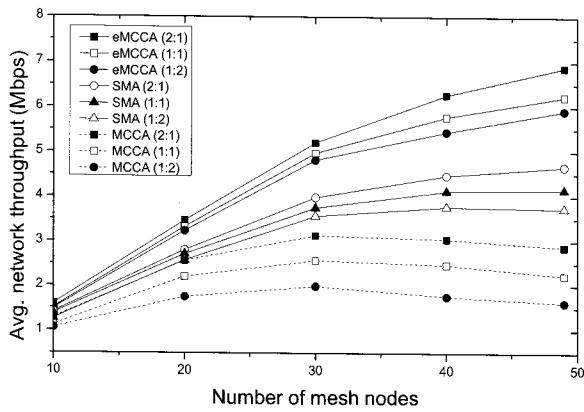


Fig. 18. Average network throughput with increasing number of nodes in the network.

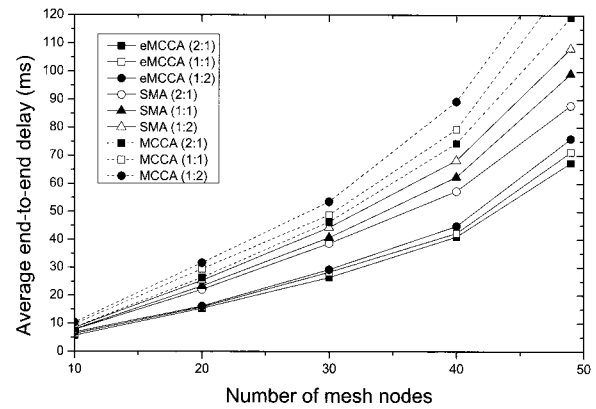


Fig. 19. Average end-to-end delay with increasing number of nodes in the network.

decrease much with increasing numbers of non-MCCA nodes. In contrast, as the number of non-MCCA nodes increased, success rates for MCCA tended to decrease due to increased collisions and the fact that the channel remained busy when MCCAOP started. The success rate for SMA was marginally better than that of MCCA because (in SMA) MCCAOP owners are allowed to continue transmission even if the MCCAOP is foreshortened. However, this can decrease the success rates of the adjacent MCCAOP owners (if there are any).

Fig. 17 shows how the collision rates of non-MCCA nodes were impacted when we increased the number of non-MCCA nodes. With both SMA and MCCA, non-MCCA nodes contend with both types of nodes and therefore, collision rates increased as the number of non-MCCA nodes increased. In contrast, non-MCCA nodes cannot contend with MCCAOP owners in the proposed eMCCA, and collisions occur only when non-MCCA nodes contend with other non-MCCA nodes. Therefore, the overall collision rate of non-MCCA nodes under the eMCCA mechanism was lower than those of SMA and MCCA.

C. Scenario 2

In this scenario, we evaluated the impact of network size on overall network performance. We gradually increased the number of nodes in the network by randomly activating nodes in the grid. However, every selection must consider one node as an MPP, and the selected nodes were assumed to be connected. Moreover, we varied the ratio of the MCCA-enabled and non-MCCA nodes in each selection to evaluate the performance in different scenarios.

We measured the following performance metrics for comparison: (1) *Average network throughput*: The sum of the sizes of all data packets received by the destination MPs in unit time; (2) *average end-to-end delay*: The average delay experienced by all successfully delivered packets; (3) *MCCAOP utilization*: The ratio of the actual transmission time used during MCCAOPs to the duration of the total reserved MCCAOPs; and (4) *packet loss rate*: The ratio of packets that were lost in the path to the number of packets generated by sources.

Fig. 18 depicts the average network throughput achieved by the eMCCA, SMA and MCCA mechanisms as we increased the number of nodes in the network. Note that in each case, the throughput got higher whenever the ratio of the MCCA-

enabled and non-MCCA nodes was set to (2:1). For both SMA and MCCA, as more non-MCCA nodes were introduced, the throughput tended to decrease due to the fact that transmission during MCCAOP was not guaranteed. Increases in non-MCCA nodes led to decreases in the success rates of the MCCAOP owners and lowered the average throughput. In case of eMCCA, average throughput did not change substantially when the ratio of MCCA-enabled and non-MCCA nodes changed, as transmission during MCCAOP was guaranteed. Therefore, average network throughput increased as the number of nodes and their loads increased.

Fig. 19 shows the average end-to-end delays for different mechanisms under increasing number of nodes. Each line of the graph represents different settings for the ratio of MCCA-enabled and non-MCCA nodes within each selection. Our proposed eMCCA mechanism outperformed others in terms of average end-to-end delay. Note that when higher numbers of non-MCCA nodes were present (i.e., the ratio was 1:2), average end-to-end delay increased sharply with the MCCA mechanism. As the number of nodes increased, traffic also increased, and contention levels got higher, which resulted in more collisions caused by non-MCCA nodes. Therefore, the number of retransmissions increased, which resulted in higher end-to-end delay. In the case of SMA, allowing extensions of MCCAOP caused adjacent MCCAOPs to be foreshortened. Moreover, like MCCA, MCCAOP owners in SMA cannot always win contention and might fail to access the channel during the reserved period. Therefore, unsuccessful packets must be retransmitted during the next reserved MCCAOP at the same node. Furthermore, as the number of nodes increases, the increase in simultaneous transmission attempts from non-MCCA nodes increases the chance of collision. All of these factors ultimately lead to increased end-to-end delays for both SMA and MCCA. In contrast, with eMCCA, collision-free transmissions without back-off mechanism is guaranteed during the reserved period. Thus, traffic flows that use MCCA-enabled MPs incur minimum delay. Moreover, the impact of non-MCCA nodes on delay is minimal, as non-MCCA nodes do not cause any unsuccessful transmissions for MCCA nodes. Therefore, variation in delay times for different ratios of MCCA-enabled and non-MCCA nodes is minimal in eMCCA, unlike those that of SMA and MCCA.

We further investigated whether real-time flows such as voice

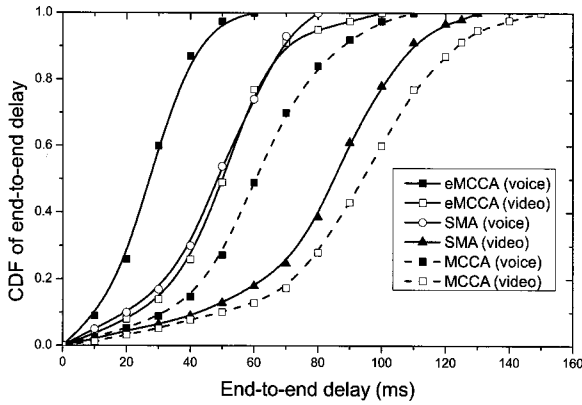


Fig. 20. CDF of end-to-end delays for the voice and video flows. The ratio of MCCA-enabled and non-MCCA nodes is set to 1:1.

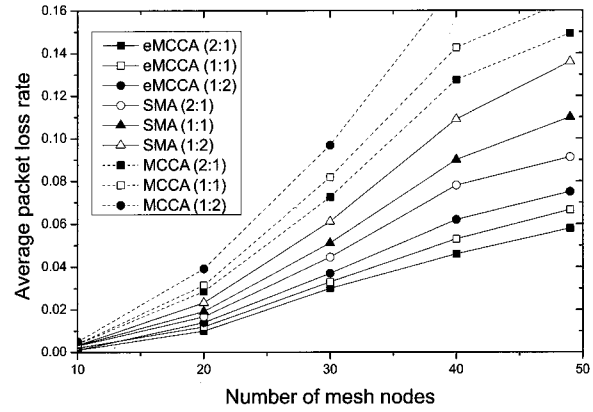


Fig. 21. PLR increases as the number of mesh nodes is increased with different ratios of MCCA-enabled and non-MCCA nodes.

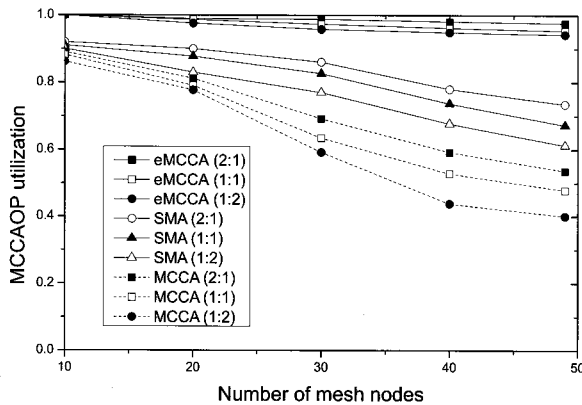


Fig. 22. Impact on MCCAOP utilization as the number of nodes is increased.

and video met delay requirements by examining the cumulative distribution function (CDF) of end-to-end delays in Fig. 20. The CDF is defined as the probability that the delay is less than or equal to a given value such as $P[T \leq t]$. As transmission during MCCAOP is guaranteed in eMCCA for both voice and video traffic, almost all packets met the delay requirements. In contrast, with the SMA, delay requirements for voice and video traffic were only met 74% and 78% of the time, respectively. The situation was still inferior with MCCA due to collisions from non-MCCA nodes and the resulting unsuccessful transmissions within MCCAOP. For MCCA, voice and video flows ended within the maximum tolerable delay only 50% and 60% of the time, respectively.

Fig. 21 shows the average packet loss rates (PLR) for all the mechanisms when we increased the number of nodes in the network. Note that eMCCA ensures collision-free access for the MCCAOP owner during a reserved MCCAOP. However, for traffic flows that use non-MCCA nodes (and hence, access the medium using EDCA), some packets may be lost due to collisions. This factor dominates PLR in eMCCA. Therefore, when non-MCCA nodes dominate a selection, packet loss rates become higher. Unlike eMCCA, packets can also be lost during the reserved MCCAOP periods when using the SMA and the MCCA. As a result, PLR increased as we increased the number of nodes in the network.

In Fig. 22, we show the MCCAOP utilization of all mechanisms. By guaranteeing access to the medium during an MCCAOP, eMCCA achieves very high MCCAOP utilization compared to SMA and MCCA, because in eMCCA non-MCCA nodes cannot gain access during an MCCAOP due to its small MIFS setting and preemption technique. Therefore, changes in the number of non-MCCA nodes do not affect MCCAOP utilization in our proposed eMCCA scheme, and utilization approaches 100%. In contrast, with both the SMA and the MCCA, MCCAOP utilization tends to decrease as the number of nodes is increased. Both the SMA and the MCCA encounter delayed initiation of MCCAOP and might not complete successful transmission during MCCAOP. As a result, MCCAOP utilization decreased. However, when MCCAOP initiation is delayed, the SMA finishes its transmission by extending its MCCAOP and achieves higher MCCAOP utilization than the MCCA.

VI. RELATED WORKS

Research on MCCA is still in its infancy. Based on earlier drafts of IEEE 802.11s, the mesh deterministic access (MDA)⁶ operation is summarized in [22] and [23]. However, a few studies have focused on the enhancement of the MCCA mechanism. Cicconetti *et al.* in [10] showed how MCCAOPs can be positioned within a mesh DTIM interval so that the amount of fragmentation can be minimized. However, as the basic access mechanism remains the same, performance is still degraded by the presence of non-MCCA nodes.

The authors in [9] proposed an enhanced beaconing scheme to improve the performance of MCCA that facilitates multiple beacon transmissions during a single beacon transmission window (BTW) and extends BTW size. This scheme ensures that MPs can complete their MCCAOP reservation during the BTW. However, advertising Tx-Rx reports only during the beacon period is not sufficient, since this will prevent MPs from using slots that become available during the DTIM, but are not advertised until the next BTW. Hiertz *et al.* [8] have proposed a mesh network alliance (MNA) approach that uses the contention free period (CFP) explicitly for MPs and contention periods

⁶MDA has been renamed to MCCA from draft D.3.03 [2]. Therefore, we use the term MCCA instead of MDA.

(CP) for legacy STAs. In MNA, MPs reserve their slots during the beacon transmission period, which is the same concept used in the distributed reservation protocol (DRP) [24] by the same authors. In [7], the authors identified problems with MCCA and proposed an improved reservation mechanism that incurs less overhead than MCCA reservation. They consecutively allocate MCCAOPs directly after the DTIM beacon, which may cause the non-MCCA nodes to starve. In addition to these, some studies have focused on mesh routing [25]–[28] and congestion control [29].

VII. CONCLUSION

In this paper, we proposed an enhanced channel access mechanism for the newly introduced IEEE 802.11s standard for WMNs. Our analyses indicated that the success probability of an MCCAOP owner during an MCCAOP decreases as the number of contending non-MCCA nodes increases. Therefore, we proposed eMCCA, a mechanism that ensures that the MCCAOP owner will have collision-free and guaranteed access to the channel during the reserved MCCAOP period, even in the presence of non-MCCA nodes. Our proposed eMCCA mechanism allows for a shorter IFS, which guarantees that the MCCAOP owner can gain access to the channel even if non-MCCA nodes simultaneously start contending. In addition, eMCCA also includes an effective preemption technique by which an MCCAOP owner can access the channel early if it finds that any probable transmission from a non-MCCA node will foreshorten the reserved MCCAOP. Finally, our simulation results demonstrated that compared to MCCA and SMA mechanisms, eMCCA significantly improves MCCAOP owner success rate, MCCAOP utilization, network throughput, and delay performance.

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