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LETTER

Centralized Contention Based MAC for OFDMA WLAN

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SUMMARY The IEEE 802.11 wireless local area network (WLAN) is the most widely deployed communication standard in the world. Currently, the IEEE 802.11ax draft standard is one of the most advanced and promising among future wireless network standards. However, the suggested uplink-OFDMA (UL-OFDMA) random access method, based on trigger frame-random access (TF-R) from task group ax (TGax), does not yet show satisfying system performance. To enhance the UL-OFDMA capability of the IEEE 802.11ax draft standard, we propose a centralized contention-based MAC (CC-MAC) and describe its detailed operation. In this paper, we analyze the performance of CC-MAC by solving the Markov chain model and evaluating BSS throughput compared to other methods, such as DCF and TF-R, by computer simulation. Our results show that CC-MAC is a scalable and efficient scheme for improving the system performance in a UL-OFDMA random access situation in IEEE 802.11ax.

key words: *wireless local area networks (WLAN), IEEE 802.11ax, orthogonal frequency division multiple access (OFDMA), UL-OFDMA random access, medium access control (MAC)*

1. Introduction

The IEEE 802.11 wireless local area network (WLAN) standards have been a tremendous success for the past 20 years [1]. However, the huge growth of mobile data traffic and multimedia smartphone applications have uncovered the need for large bandwidth and high data rates for next generation WLANs.

To address the future demand for WLAN, the IEEE 802.11ax task group ax (TGax) and the high-efficiency wireless LAN (HEW) study group have been working on a new amendment called IEEE 802.11ax-2019 [2]. The goal of 802.11ax is to satisfy the forecasted user demands for the next decade. The use cases of IEEE 802.11ax mainly consist of densely populated access points (APs) and stations (STAs).

IEEE 802.11ax uses orthogonal frequency division multiple access (OFDMA) systems [1], [3]. OFDMA allows multiple users to share the single channel and enhances bandwidth efficiency with proper radio resource allocation and scheduling. OFDMA proved its technical feasibility and spectrum efficiency in IEEE 802.16e WiMAX, 3GPP long-term evolution (LTE), and LTE-advanced (LTE-A) standards. On the other hand, the introduction of new PHY technology creates important challenges in IEEE 802.11ax MAC design.

TGax decided to introduce a new uplink OFDMA (UL-OFDMA) transmission mode, UL-OFDMA random access. However, to fully utilize the PHY layer advantages of OFDMA, a new MAC protocol which allows multiple uplink STAs for UL-OFDMA is required. There were some suggestions using a trigger.

Baron et al. proposed a MAC protocol using trigger frame-random access (TF-R) discussed in TGax in 2015 [4]. In Baron's method, STAs directly transmit uplink data according to their backoff counter. As a consequence, distributed coordination function (DCF) is carried out on each resource unit (RU), so it is hard to expect performance gain in the presence of large number of STAs.

In the other direction, AP plays a central role in RU allocation for UL-OFDMA. The more information about UL data AP has, the more efficient allocation. In the 802.11ax draft standard, information gathering operation for UL data is called buffer status reporting (BSR).

Ghosh's TF-R [5], OMAX [6], and HMAC [7] are similar to one another with respect to the way how AP gathers BSR information. However, their performance is limited by the number of RUs, because at most as many STAs as the number of RUs succeed in reporting their buffer status. The use cases of 802.11ax, hundreds of STAs competing using UL-OFDMA, make it difficult to enhance performance when the number of RUs is not comparable to the number of active STAs.

Ghosh et al. proposed a method using TF-R in 2015. In IEEE 802.11ax spec framework, it has been the most approved suggestion in TGax discussion so far [3]. In Ghosh's method, STAs try to report their buffer status once at the same time, and contend in the frequency domain by selecting RU according to their backoff counters.

In this paper, we propose a centralized contention-based MAC for OFDMA WLAN (CC-MAC), which extends the number of reporting STAs significantly compared to Ghosh's method, since CC-MAC gathers BSR over multiple time slots. This leads to consecutive UL-OFDMA transmissions without overhead, which increases the system throughput. The detailed operation of CC-MAC is described in Sect. 3.

2. System Model

IEEE 802.11ax adopted many novel PHY techniques. To

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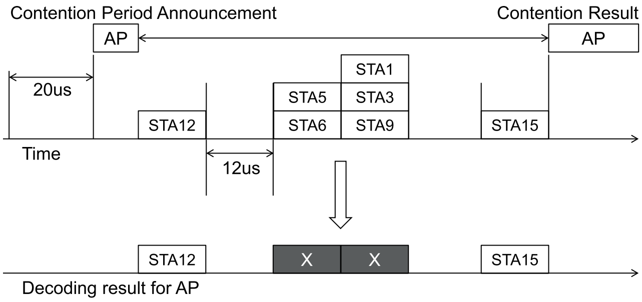

Fig. 1 Illustration of CC-MAC. Contention period is announced by a CPA frame and contention result is announced by a CR frame. Each STA selects a slot from range $[0, N_T]$ to send an STA AID signal. After the CR frame, multiple winners can transmit data frames simultaneously using UL-OFDMA.

do this, PHY parameters and numerology were changed in IEEE 802.11ax [8]. The most notable difference is the increased fast fourier transform (FFT) size. For a 20MHz channel, IEEE 802.11ax uses 256 subcarriers instead of 64 subcarriers. To offset the increase of subcarriers, 802.11ax uses 12.8μs OFDM symbol duration instead of 3.2μs. A 20MHz channel can have up to 9 resource units for 9 simultaneous OFDMA transmissions.

The IEEE 802.11ax simulation scenarios published by TGax describe main usage scenarios up to 200 STAs per AP. In this paper, we assume a basic service set (BSS) with one AP and 200 STAs for our example. This BSS only contains 802.11ax devices with OFDMA capability.

OFDMA MAC protocols including CC-MAC rely on the initiating behaviors of AP (Fig. 1). To start the UL-OFDMA simultaneous transmission, a trigger from AP is essential. For example, methods from both Baron [4] and Ghosh [5] also uses the TF-R frame as a trigger. Also, it should be noted that to enable UL-OFDMA random access mode, every device in the BSS should support OFDMA capability.

3. Proposed Method

The OFDMA transmission is composed of downlink (DL) and uplink (UL) operations. For both operations, the AP and STAs need to exchange the channel allocation information that indicates which devices use which subchannels prior to the transmission. The downlink OFDMA operation uses HE-SIG-B field in the preamble for this purpose [3]. The AP communicates which STAs should receive from which subchannels via elements in the HE-SIG-B field.

However, UL-OFDMA is more complicated than DL-OFDMA. To simultaneously transmit multiple frames from multiple STAs, the AP needs to broadcast the synchronization information for the STAs. In 802.11ax, trigger frame (TF) and TF-R conduct synchronization. As we can see later, the system performance of UL-OFDMA random access heavily relies on the behavior of MAC protocol.

The behavior of CC-MAC is described here. There are two control frames we introduce in this paper, contention period announcement (CPA) and contention result (CR). We assign a type value of 01 (Control) and subtype value of 1000 and 1001 to these frames. The contents of control frames are illustrated in Fig. 2. The contention period has a fixed amount of time slots (N_T), which can be set by the AP. Whenever a UL-OFDMA random access is required, the AP sends a CPA frame that replaces the TF-R frame. The STAs with uplink data choose a random slot number from the range $[0, N_T]$ and send an STA AID signal in that time slot. The AP listens to the channel through the whole contention period, and collects decodable information from the STAs. There can be multiple winner STAs at the end of a contention period as can be seen in Fig. 1. Then, the AP broadcasts winners in the CR frame. Thus, the STAs can send their uplink frames simultaneously via UL-OFDMA.

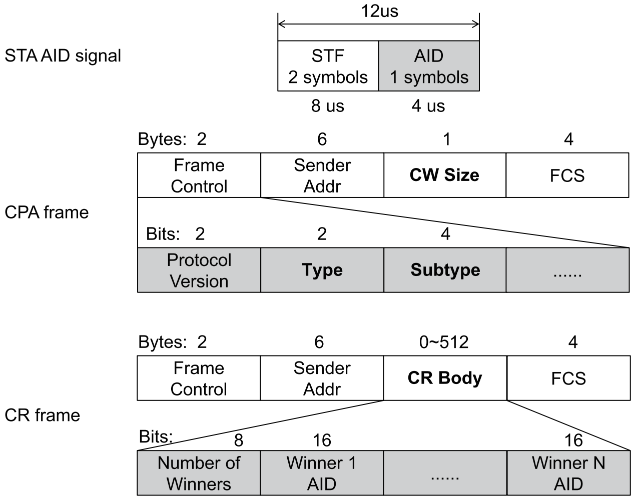

Fig. 2 Illustration of CPA, CR, and STA AID signal used in CC-MAC.

The number of successful STAs (N_S) in the contention period can be one of two cases. In the first case, it is larger than or equal to 0 and smaller than or equal to the number of RUs ($0 \leq N_S \leq N_{RU}$). In this case, AP assigns N_S to the 'number of winners' field in the CR frame, and lists the STA AIDs of successful STAs in ascending order. Because both N_S and N_{RU} are integers, perfectly equal distribution of RU is impossible. However, RUs can be assigned to each STA contiguously and distributed equally in the most possible way. For example, if $N_S = 4$ and $N_{RU} = 7$, then the RU assignment is $\{1, 1, 2, 2, 3, 3, 4\}$. If $N_S = 2$ and $N_{RU} = 4$, then the RU assignment is $\{1, 1, 2, 2\}$.

Second, if the number of successful STAs is larger than the number of RUs ($N_S > N_{RU}$), then AP assigns N_S to the 'number of winners' field in the CR frame, and lists the STA AIDs of successful STAs in ascending order. In this case, the number of listed STA AID is as same as the number of RUs because the number of RUs is the upper limit of OFDMA simultaneous transmission. Then listed STAs transmit their uplink data. At the end of UL-OFDMA transmission, AP broadcasts new CR frame with new $N'_S = N_S - N_{RU}$ after waiting 16μs. With this procedure, CC-MAC handles a large number of successful STAs from the contention period equally and efficiently.

To elaborate further, we present the STA AID signal used in CC-MAC. We modified the SIGNAL field of the PHY preamble to convey the 16-bit STA AID information. Because of this signal, we increased the slot time from $9\mu s$ to $12\mu s$ in CC-MAC. We researched the PHY layer details of IEEE 802.11ax and concluded that we can reasonably send 16-bit information in $12\mu s$ time slot. If there is only one STA AID signal in a given time slot, then the AP can read STA AID information; and that STA becomes one of multiple winners. If there are more than one STA AID signals in a given time slot, then the AP cannot read any information; and those STAs become collided STAs.

The important difference between DCF and CC-MAC is that CC-MAC can have multiple winners in one contention round. It enables the consecutive DL and UL operations with less contention overhead. For example, if CC-MAC has 9 winners for one contention period, then it can save 8 DIFS + 8 SIFS + 8 ACK + 8 DCF contention overhead time for the cost of one CC-MAC contention period. Moreover, CC-MAC contention period is fixed length. Thus it scales very well with a high number of STAs in the BSS.

To fully utilize the throughput potential of CC-MAC, choosing the best N_T for given number of STAs in the BSS is very important. The expected number of winner STAs is mathematically calculated in the following section.

4. Analysis

The two most important parameters in CC-MAC are the number of STAs participating in the contention (N_{STA}) and number of total contention slots (N_T). It is of importance that the AP assigns the number of contention slots to increase the expected number of successful STAs (N_S) and decrease the collisions. Therefore, we chose a stochastic process approach in this paper to evaluate the performance numbers prior to the computer simulations.

We present a discrete Markov chain according to our system model explained in Sect. 2 (Fig. 3). A state is defined as a set of 3 variables, $\{N_S, N_C, N_E\}$. All three variables describe the contention status of the given BSS. For example, N_S is the number of successful Tx slots in the BSS containing only one STA AID. N_C is the number of collided slots containing multiple STA AIDs. N_E is the number of empty slots. By definition, we can obtain $N_T = N_S + N_C + N_E$.

As shown in Fig. 4, a state has only three possible state transition probabilities for each step. This is because in any given BSS contention state, a new STA can only introduce three effects to the contention.

i) transition to down: If a new STA chooses an empty slot, then, it increases N_S by one and decreases N_E by one.

ii) transition to right: If a new STA chooses a previously successful slot, then it decreases N_S by one and increases N_C by one. The previously successful slot becomes a collided slot.

iii) transition to itself: If a new STA chooses a previously collided slot, then, it does not change the slot status of the BSS. This is because any number of collided STA AIDs in the same slot is just one collision to the AP.

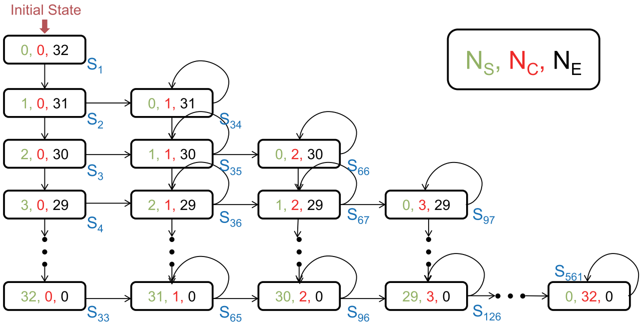

Fig. 3 Analytical model using Markov chain for CC-MAC with $N_T = 32$. Each state represents the status of the contention period. Each state transition means the participation of a new STA.

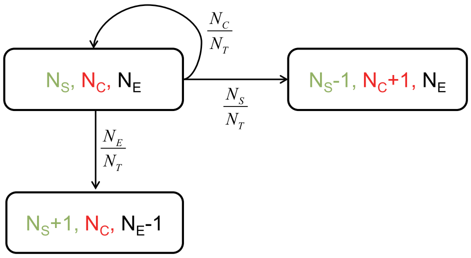

Fig. 4 State transition diagram of Markov chain for CC-MAC. There are only three cases of state transition for each state.

A transition step in our Markov chain represents a participation of a new STA. This means that if we have an initial state vector ($\vec{v_i}$) and state transition matrix ($\mathbf{P}$), then, we can compute the final outcome state vector ($\vec{v_o}$) as follows:

$$\vec{v_o} = \vec{v_i} \cdot \mathbf{P}^{N_{\text{STA}}}$$

It should be noted that the ordering of participation and ordering of the contention slots have no effect on the contention result at all.

To define the state vector and state transition matrix, we need to develop a numbering scheme for our Markov chain. It should arrange all state numbers (S_x) from S_1 to $S_{\max}$ linearly without any holes.

$$\begin{aligned} S_{\max} &= 1 + \frac{{N_T}^2 + 3N_T}{2} \\ S_x &= N_S + 1 + \frac{-{N_C}^2 + 3N_C + 2N_C N_T}{2} \end{aligned} \tag{1}$$

Obtaining S_x, when you have N_S and N_C, is simple if we consider $N_S \leq N_T$ and Eq. (1). Thus, we have a bidirectional mapping function for every state.

For this analysis, we calculated $\vec{v_o}$ for various N_T and N_{STA}, as shown in Fig. 5. To obtain the expected number of N_S, which is denoted as E[Ns], we should perform the following computation:

$$\text{E[Ns]} = \sum_{i=S_1}^{S_{\max}} N_S[i] \cdot \vec{v_o}[i],$$

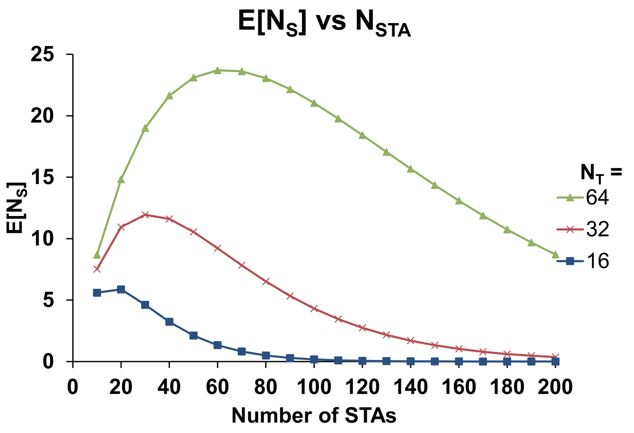

Fig. 5 Computation result of the proposed Markov chain analysis. E[Ns] denotes the expected number of STAs which had successfully transmitted for a contention period.

where $N_S[S_x]$ denotes the N_S value of given state S_x and $\vec{v_o}[S_x]$ denotes the x-th element of state outcome vector $\vec{v_o}$.

5. Evaluation

We conducted computer simulations to compare the performance of CC-MAC to existing contention-based MAC protocols, such as IEEE 802.11 DCF, TF-R from Baron et al. [4], and TF-R from Ghosh et al. [5]. Owing to the lack of complete and accessible OFDMA simulators for the IEEE 802.11ax draft standard in the research field, we developed an event-driven OFDMA MAC simulator in Visual C# 2013 with .NET Framework 4.5 on the Windows 7 operating system. The simulation parameters are given in Table 1.

As can be seen in both the mathematical analysis and computer simulation, the proposed CC-MAC protocol has throughput advantage, compared to existing UL-OFDMA random access MAC protocols. This is because CC-MAC obtains multiple winners for each round of contention, and exploits this via consecutive UL-OFDMA operations without intermittent MAC overhead. In the $N_{\mathrm{STA}} = 200$ case, CC-MAC with $N_T = 64$ achieved 119.15% throughput improvement compared to DCF, and 25.35% throughput improvement compared to Ghosh's TF-R.

We would like to discuss the difference between both TF-R methods here. Currently, the IEEE 802.11ax draft standard has incorporated Ghosh's TF-R for the UL-OFDMA random access method [3]. The draft standard allows DCF and Ghosh's TF-R for uplink operations in OFDMA. The TF-Rs from both Baron and Ghosh tried to reduce the consecutive collisions that are very frequent in DCF. However, when collision between multiple STAs occurs, Baron's TF-R retransmits the whole data frame while Ghosh's TF-R retransmits only the TF-R frame. Considering that the TF-R frame (less than 250 bytes) is much shorter than the data frame, especially in a frame aggregated situation, the performance difference between Ghosh's and Baron's TF-R is understandable.

Table 1 Simulation parameters for IEEE 802.11ax BSS.

Name	Explanation	Value
BW	Channel bandwidth	20MHz
MCS	Modulation and Coding Scheme	256-QAM, 3/4
$\mathrm{SYM}_{\mathrm{GI}}$	OFDMA symbol duration with GI	13.6μs
L_{data}	Data length for aggregated frame	36864 bytes
L_{ACK}	Compressed Block ACK frame length	130 bytes

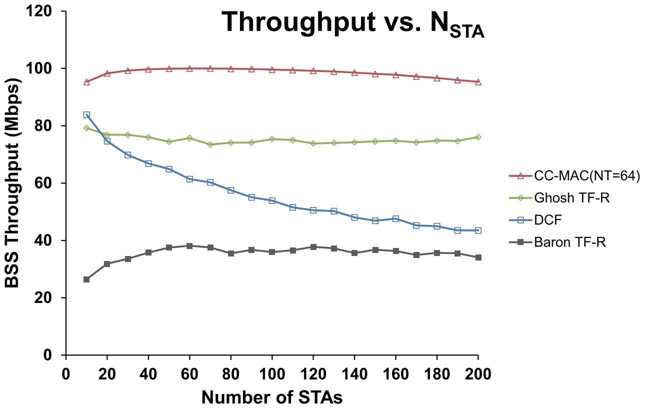

Fig. 6 Performance evaluation graphs of DCF, Baron's TF-R, Ghosh's TF-R, and CC-MAC with $N_T = 64$.

As shown in Fig. 6, the benefit of having more winner STAs per contention period outweighs the cost of having a higher contention period time slot overhead. Other methods cannot collect the information of multiple uplink STAs at once, while CC-MAC is purposely designed to exploit consecutive uplink OFDMA operations.

6. Conclusion

In this paper, we designed and presented CC-MAC, which can fulfill the throughput potential of OFDMA physical characteristics in a UL-OFDMA random access situation. We performed both mathematical analysis and computer simulations to evaluate the performance of CC-MAC compared to other methods. Finally, we discussed the reasons of the performance improvement of CC-MAC and suggested that our proposed method is the best method for UL-OFDMA random access in the IEEE 802.11ax draft standard.

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