



Performance analysis of trigger frame in enhanced UL and DL MU MIMO transmissions

Hyunhee Park¹

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Abstract

In an Internet-of-Things (IoT) environment, congestion and scarcity problems may occur because many mobile stations (STAs) access wireless networks simultaneously. The IEEE 802.11ax/802.11be standards for large-scale wireless communications have defined a trigger frame (TF) to control multiple STAs. During resource allocation, the downlink (DL) transmission is divided in a control period from the access point (AP) to multiple STAs. The resource allocation (RA) is then assigned to an uplink (UL) transmission by a TF and a DL period from the AP to STAs. However, because the DL transmission should be considered separately in terms of the control and DL periods, it is necessary to analyze the DL transmission. We propose a scheduled MU transmission (SMT) algorithm for enhanced UL and DL MU MIMO transmissions. In this study, we analyze and systematically model medium access control (MAC) performance when the DL transmission is divided in the control and data periods when the UL coexists with the DL data transmission. To achieve this, we mathematically analyze the time-efficient throughput, estimate the transmission and collision probabilities for wireless local area network (WLAN) STAs, and generalize the transmission interval. In addition, we propose an access category (AC) for the TF that is defined in the DL transmission. All data transmissions are defined as the ACs for basic channel access, but the AC is not defined for the TF. Therefore, we clarify the transmission by defining the AC of the TF to control the UL transmissions of various STAs. Evaluation results demonstrate that the SMT algorithm can improve the MAC throughput by up to 70% – 87% compared to UL and DL MU MIMO transmissions.

Keywords DL MU MIMO · UL MU MIMO · Trigger frame · Markov chain

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✉ Hyunhee Park
hhpark@mju.ac.kr;

¹ Department of Information and Communication Engineering, Myongji University, Yongin, South Korea

1 Introduction

The opportunities in recent multimedia along with emerging Internet-of-Things (IoT) applications, such as cloud-of-things, intelligent fog computing, trust monitoring, and autonomous vehicles, are limited by the finite capacity of wireless communication stations (STAs). The IEEE 802.11 wireless local area network (WLAN) systems have been studied with respect to congestion and scalability. In the case of the IEEE 802.11ax standard, it is necessary to analyze congestion and scalability because the IoT environment with multiple STAs is defined as an application case of this standard [11]. IEEE 802.11ax supports uplink (UL) multiple user (MU)–multiple-input and multiple-output (MIMO) and massive downlink (DL) MU–MIMO. This study focuses on the potential of massive MIMO systems to improve UL MU transmission performance with hidden terminal problems in IEEE 802.11ax. Existing proposals for UL MU–MIMO in WLANs adopt the legacy contention-based distributed coordination function (DCF) along with the exchange of request-to-send/clear-to-send (RTS/CTS) control frames to avoid the hidden terminal problem [22]. However, the effective throughput obtained in the MAC layer using existing techniques is limited when the number of concurrent streams increases. Accordingly, in the IEEE 802.11ax MAC sublayer, the UL MU transmissions are initiated by an AP-coordinated trigger operation [4, 9]. Furthermore, several massive MIMO works are based on system level simulations, and a few analytics that allow for extra comparisons between various coexistent mechanisms, such as long-term evolution (LTE) and WLAN systems. Recently, stochastic geometry was used to model the coexistence of dense Wi-Fi networks. In particular, in [5] and [13] the coverage and throughput performance of coexisting LTE and Wi-Fi networks were derived with the use of stochastic geometry, where the effect of sensing thresholds and transmit power were investigated. However, Bhorkar et al. [5] and [13] considered only the DL Wi-Fi transmissions of Wi-Fi APs. Moreover, the analytical formulas were derived from the legacy 802.11 Wi-Fi WLAN.

In this study, we consider the coexistence of DL MU and UL MU transmissions in the IEEE 802.11ax Wi-Fi standard [2–5, 9, 13]. In particular, we consider MAC enhancements associated with the IEEE 802.11ax standard for the purpose of supporting UL MU quality-of-service (QoS) requirements for applications with the use of Wi-Fi networks, especially in dense environments. Until now, the focus has been on mathematical modeling analysis which has considered UL and DL transmissions on the same channel link [1, 15, 20]. For resource allocation, the DL transmission can be divided into a control period from an AP to multiple STAs, where resources are allocated to UL transmissions by a trigger frame (TF) and a DL period. Most studies have analyzed and modeled the performances of UL and DL transmissions. However, because the DL transmission should be considered as the control and DL periods, it is necessary to analyze the DL transmission separately. In this study, we analyze and perform systematic modeling of the medium access control (MAC) performance when the DL transmission is divided into two periods and the UL transmission coexists with the DL transmission. To achieve this, we propose a scheduled MU transmission (SMT) algorithm for enhanced UL and DL MU MIMO transmissions. In addition, we mathematically analyzed the time-efficient throughput, transmission and collision probabilities for WLAN and STAs, and generalized the transmission interval. The control period of DL MU transmission has a TF that the AP sends for the UL MU transmission. In this case, the TF should be sent based on the channel access rule; however, there is no clear definition of the channel access for the TF. For example, if the transmission of the TF fails, the STA will continue to wait for the TF. This is because the TF is the control frame transmitted by the AP. Thus, the acknowledgement (ACK) frame of the TF is not defined. For instance, a

beacon frame is defined as the control frame which does not receive the ACK frame. As a result, as the AP has set up the UL transmission of the STA, it will no longer send the TF for the resource unit (RU) allocation. At the same time, STAs that do not receive the TF will waste time waiting for the TF assigned to their RUs to maintain UL transmissions.

Furthermore, in the IEEE 802.11ax standard, which recently defined the draft specification 4.0, the access category (AC) for the TF transmitted by the AP and the corresponding enhanced distributed channel access (EDCA) were not defined [11]. This can lead to many problems related to channel access owing to uncertainty. For instance, when the control frame is defined as the best-effort (BE) category that is the lowest priority, the TF can define the EDCA for the channel competition in the BE category. However, as the TF has a low priority, the priority of the UL transmission will decrease. Conversely, if the TF is defined as the voice (VO) category, that is, the highest priority, the UL transmission also has a high priority regardless of the DL MU transmission. Therefore, we define an appropriate channel access mechanism of the TF in the DL transmission. In the case of the TF, it is an important control frame sent to allocate an RU when many STAs want to transmit UL data. At the same time, the AP can send the TF, including a large amount of user information [11]. When the TF length increases considerably because of a large amount of user information, the AP should control the DL and UL transmissions. In this study, we define the allocation of an appropriate AC for the TF by considering a virtual AP queue. We also define a model in which three periods (i.e., control, DL, and UL) coexist, and analyze the channel access probability, collision probability, and throughput. Moreover, we define the channel AC of the TF and propose a model to improve the overall throughput performance. The key contributions of this paper are as follows:

- By following the control period for transmission of TF, we provide new performance analysis that is valid for multiple periods, and propose the SMT algorithm for the DL MU and UL MU transmissions
- We implement extensive simulations to evaluate the MAC layer coexistence of the control period and the data frame transmission periods (e.g., DL and UL), and validate our analytical results
- The TF confirms the priority of the UL transmission of the corresponding STAs. Therefore, we propose a new definition for the AC and EDCA mechanism for the TF according to UL transmission

The remainder of this paper is organized as follows: Section 2 describes the TF and UL MU and DL MU transmissions as a coexistent system model, and Section 3 presents the performance analysis for the coexistence model assuming three types of periods. Section 4 defines the proposed AC of the TF in the EDCA channel contention. Section 5 provides extensive simulation and numerical results. Conclusions are presented in Section 6.

2 System model

We consider a model in which WLAN STAs sharing an unlicensed spectrum allocate transmission intervals through channel competition, and transmit desired data. In this model, the UL data transmission (UDT) and DL data transmission (DDT), which coexist with the DL control-frame transmission (DCT), are modeled in a saturated environment as shown in Figure 1. In WLAN EDCA, the arbitration interframe spacing (AIFS), transmission duration, initial contention window (CW) size, and back-off period are defined by different access categories [8, 21]. To consider this environment, we assume that the WLAN UL and DL transmissions have different CW sizes. In this model, we do not consider unsaturated

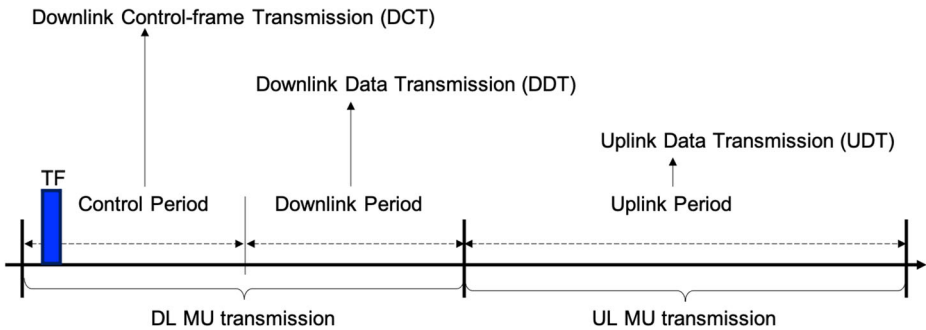


Figure 1 TF, DL MU, and UL MU transmissions

states where buffers are idle. This is because IEEE 802.11ax assumes a traffic model in a dense environment.

In existing solutions for UL MU-MIMO transmission in WLAN, the airtime occupied by the multiple-round exchanges of RTS/CTS frames and the associated back-off periods linearly increase as the number of concurrent streams supported by the AP increase [10, 17]. Therefore, in IEEE 802.11ax, the AP is provided with the means to coordinate the various UL MU transmissions. Specifically, the STAs attempt to report the amount of buffered data they have to the AP; based on this information, the AP determines the duration of the UL MU transmission and allocates resources to each solicited STA with the use of the TF operation. To guarantee time synchronization, after a short inter-frame space (SIFS), the solicited STAs perform UL MU transmission in response to the receipt of the TF.

We analyzed the transmission of the TF that is responsible for DL transmission for the AP. Figure 2 depicts the process where the AP determines the back-off counter before sending the TF, and performs a clear channel assessment (CCA) to assess if the channel is idle. In the proposed model, if the channel is determined to be idle by the initial CCA, the AP calls for an extended CCA to be performed instead of directly transmitting the TF. The initial CCA interval is allocated a DCF inter-frame space (DIFS) length, which is $34\mu\text{s}$ [11]. If it is determined that the channel is idle, the extended CCA checks once more if the channel is idle. In this case, the extended CCA is allocated to the SIFS length [7]. The reason is attributed to the fact that as the channel has been evaluated to be idle by the initial CCA, it can transmit the TF immediately after it waits for the SIFS, before other channel connections begin. The TF does not receive an ACK in its response. Thus, we can define the timeout to verify the success or failure of the TF. The time from the transmission of the TF to the reception of the UL data from the STA is defined as t . If the UL data are received within the defined timeout (T_{out}), the transmission of the TF is successful. In this case, $t < T_{out}$ can be defined. At this time, the back-off counter can be adjusted to CW_{min} . If the UL data are not received within the defined T_{out} , the transmission of the TF can be judged as a failing transmission. In this case, $t \geq T_{out}$ can be defined. The back-off counter is doubled and when the channel is idle again, the TF is retransmitted when the back-off counter becomes zero.

Thus, we defined the channel access and data transmission of IEEE 802.11ax in terms of DCT, DDT, and UDT in Figure 1. In particular, DDT is transmitted by the AP for the DL data. Furthermore, the AP may send a TF for the RU allocation of the STA in DCT. The STA may send UL data in UDT based on the RU allocation of the TF. In the case of the TF and the DL MU PLCP protocol data unit (PPDU) sent by the AP, the tendency is different.

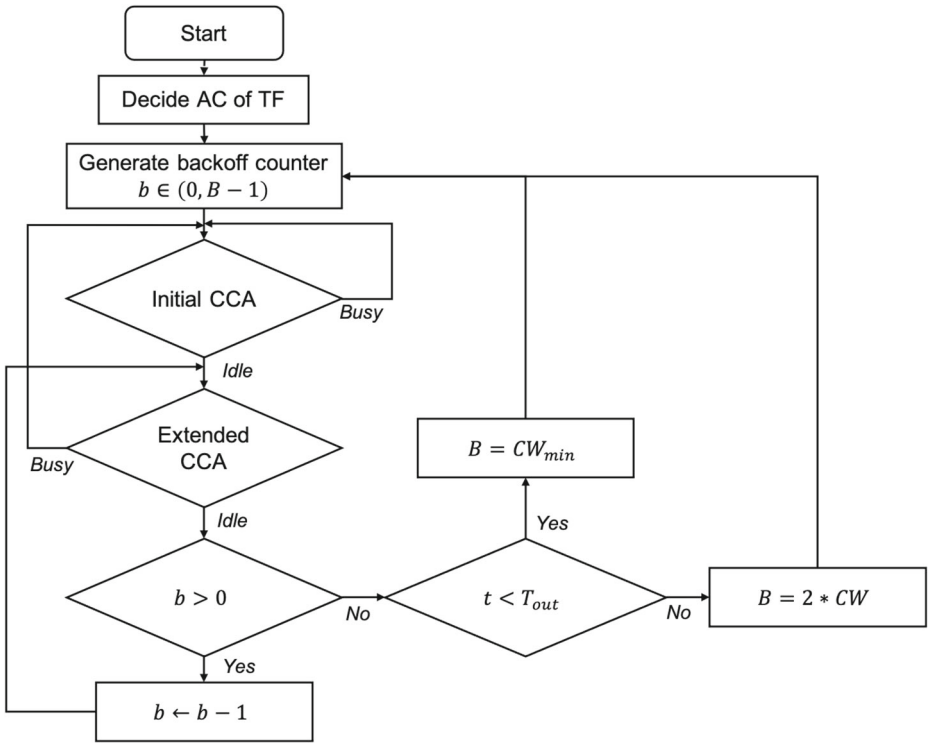


Figure 2 TF transmission flowchart

We now define the following: (1) DCT for the transmission of the TF, (2) DDT for DL data, and (3) UDT for UL data by the STAs.

Furthermore, in the case of the TF transmitted by the AP, the EDCA protocol is not defined. This means that the AP may set the AC value to the highest value (for example, voice traffic) according to specific AP vender or lowest value (for example, best-effort traffic) regardless of the buffer status. Therefore, the value of the AC for the TF is still left ambiguously undefined. In this study, we define the AC that is to be allocated for TF transmission according to the amount and type of UL MU transmission obtained from the buffer status report (BSR) frame.

3 Scheduled MU transmission algorithm

3.1 Markov model of TF transmission procedure

Based on Figure 3, we provide a Markov chain-based model for DCT for TF transmission. In the EDCA protocol, the back-off length is defined as the maximum back-off stage and does not increase after the maximum length is achieved [6, 21]. The maximum back-off stage at this time is defined as B_m . If the channel is idle at each stage for an extended CCA duration, it is denoted as T_{CCA_e} . When the back-off counter is reduced to zero, a TF transmission begins. It appears that the Markov model in Figure 3 is similar to the model

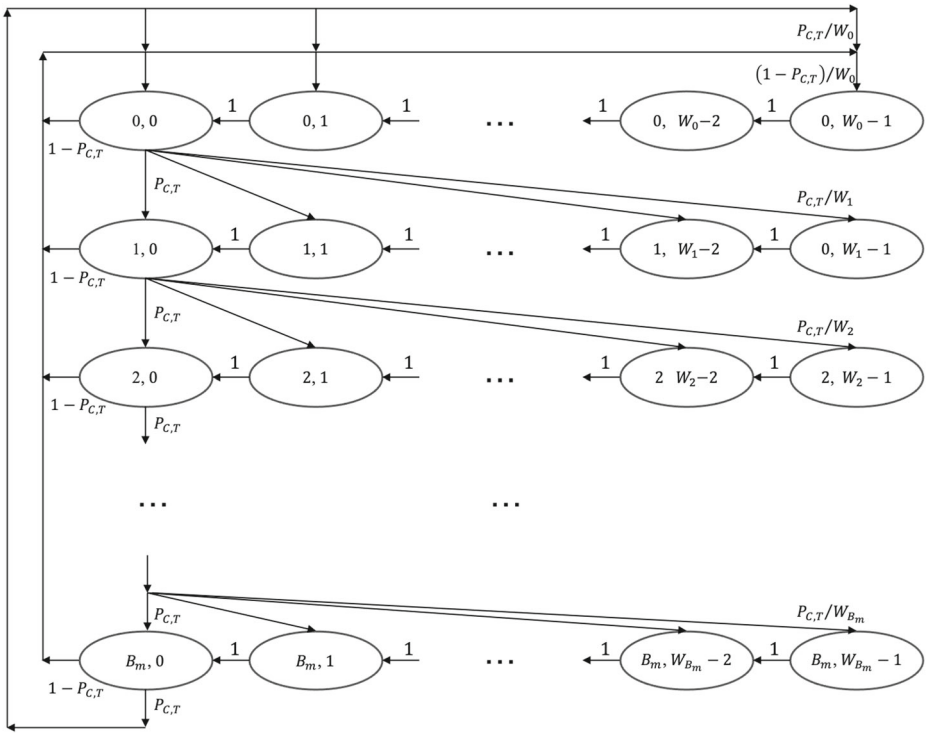


Figure 3 Markov chain model of control-frame transmission (DCT)

given by [6, 12, 16]. To allow an MU MAC protocol, IEEE 802.11ax should adopt a scheduled coordinated method. Coordinated implies that STAs should exchange control frames to reserve the channel. In addition, scheduled means an AP should trigger the concurrent transmission. To reduce the overhead transmission time, the requests for an UL transmission may be inserted in a frame. The STAs send their common frame following the addition of one bit in the frame header, which indicates they have more data to send. After gathering requests from the STAs, the AP groups these STAs and triggers simultaneous access. A TF is then sent as a control frame to request that STAs transmit UL MU data. This allows the STAs to start their UL transmissions in a synchronized manner in Figure 3. Once the control frame reserves the channel, the other STAs are silenced, thus avoiding collisions. Interestingly, the IEEE 802.11ax specification does not solve the channel access procedure of the AP. Alternatively, the access procedure for the AP is open so that AP manufacturers can arbitrarily define that parameter. Therefore, the access procedure of the AP is not clear and the channel access procedure of IEEE 802.11ax is ambiguous.

The TF could be sent after the channel idle duration $T_{CCA_i} + T_{CCA_e}$, before counter decrement. We assumed that $T_{CCA_i} = T_{DIFS}$, where T_{DIFS} is the DIFS duration [6]. The probability $P_{c,T}$ is the probability of experiencing a collision when a TF is transmitted because the channel is idle. Finally, DL transmission for the TF is performed when the back-off counter becomes zero. δ_I is defined as T_{CCA_e} which is the idle slot duration. In Figure 4, the transmission of the other TF is prioritized compared with the other UL MU and DL MU transmissions. We assumed that the DCT for the TF transmission is shorter

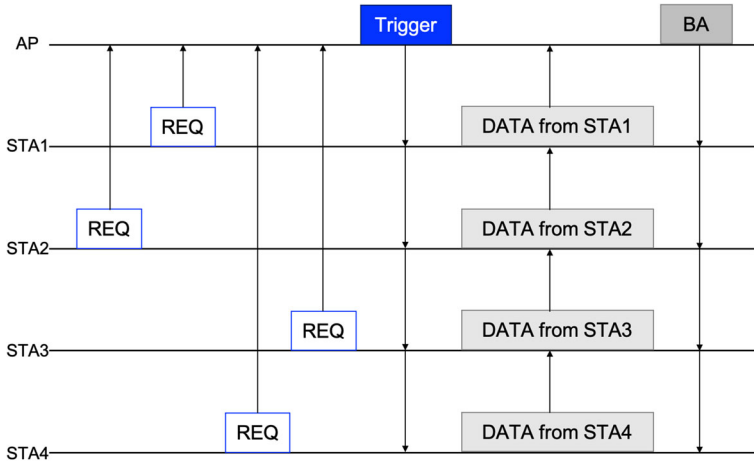


Figure 4 UL MU MIMO trigger procedure

than DDT for DL MU data transmission. The TF only carries information required by the responding STAs that identifies STAs participating in the UL MU transmissions. It assigns RUs to these STAs as the MU-MIMO transmissions in the UL direction.

3.2 Stationary probability and throughput analysis

Based on the Markov chain model of the DL transmission for the TF in Figure 3, we define the DL transmission of the TF, the DL MU transmission from the AP to the STAs, and the UL MU transmission from the STA to the AP, respectively. The conditional state transition probabilities for these are as follows,

$$P(0, k|b, 0) = (1 - P_{C,T}/W_0), b \in [0, B_m - 1], \tag{1}$$

$$P(0, k|B_m, 0) = P_{C,T}/W_0, \tag{2}$$

$$P(b, k|b, k + 1) = 1, b \in [0, B_m], k \in [0, W_b - 2], \tag{3}$$

where W_b is the CW size when the back-off stage is b , $b = 0, 1, \dots, B_m$, $k \in [0, W_b - 1]$ is the back-off counter value, and B_m is the maximum back-off stage for the TF.

We define $\pi_{b,k}$ as the probability of the Markov state of (b, k) . Using (1) to (3) and the total probability of all states, the following results can be obtained by [8, 10].

$$\pi_{b,0} = P_{C,T}^b \pi_{0,0}, b \in [0, B_m], \tag{4}$$

$$\pi_{b,k} = \frac{W_b - k}{W_0} \pi_{b,0}, k \in [0, W_b - 1]; b \in [0, B_m]. \tag{5}$$

Using the fact that the total probability of all states is unity, we obtain

$$\sum_{b=0}^{B_m} \sum_{k=0}^{W_b-1} \pi_{b,k} = 1, \tag{6}$$

$$\pi_{0,0} = \left[\frac{1}{2} \sum_{b=0}^{B_m} P_{C,T}^b (1 + W_b) \right]^{-1}. \tag{7}$$

In addition, the transmission probability that the AP can transmit to each TF is as follows,

$$\tau_T = \sum_{b=0}^{B_m} \pi_{b,0} = \pi_{0,0} \frac{1 - P_{C,T}^{B_m+1}}{1 - P_{C,T}} = \frac{2 \left(1 - P_{C,T}^{B_m+1}\right)}{\left(1 - P_{C,T}\right) \sum_{b=0}^{B_m} P_{C,T}^b \left(1 + W_b\right)}. \tag{8}$$

The joint stationary probability distribution of DL transmissions for the TF and DL transmission for data by the AP will follow. To do this, we define the failed transmission probability of the TF, the failed transmission probability of the DL MU transmission, and the failed transmission probability of the UL MU transmission as $P_{C,T}$, $P_{F,D}$, and $P_{F,U}$, respectively. The channel access probabilities of these corresponding transmissions are defined as τ_T , τ_D , and τ_U , respectively. In addition, the initial CW sizes are expressed as W_0 , $W_{0,D}$, and $W_{0,U}$, respectively, and the maximum back-off stages are expressed as B_m , B_D , and B_U , respectively. Based on [21], the transmission probability of the DL MU transmission and the transmission probability of the UL MU transmission are defined according to (9) and (10), respectively,

$$\tau_D = \frac{1}{1 + \alpha_D \left(\sum_{b=0}^{B_D} P_{F,D}^b (2^b W_{0,D} - 1) - \left(1 - P_{F,D}^{B_D+1}\right)\right)}, \tag{9}$$

$$\tau_U = \frac{1}{1 + \alpha_U \left(\sum_{b=0}^{B_U} P_{F,U}^b (2^b W_{0,U} - 1) - \left(1 - P_{F,U}^{B_U+1}\right)\right)}, \tag{10}$$

where α_D is $(1 - P_{F,D})/2 \left(1 - P_{F,D}^{B_D+1}\right)$ and α_U is $(1 - P_{F,U})/2 \left(1 - P_{F,U}^{B_U+1}\right)$. The failed transmission probability of DL transmission for the TF and the failed transmission probabilities of the MU transmissions for the DL and UL data are derived as follows:

$$P_{F,T} = 1 - (1 - \tau_T)^{n_T-1} (1 - \tau_D)^{n_D} (1 - \tau_U)^{n_U}, \tag{11}$$

$$P_{F,D} = 1 - (1 - \tau_D)^{n_D-1} (1 - \tau_U)^{n_U} (1 - \tau_T)^{n_T}, \tag{12}$$

$$P_{F,U} = 1 - (1 - \tau_U)^{n_U-1} (1 - \tau_D)^{n_D} (1 - \tau_T)^{n_T}, \tag{13}$$

where τ_T , τ_D , and τ_U are given by (8), (9), and (10), respectively. The iterative search method used to solve the transmission and collision probabilities has been used often in literature [8, 10]. Therefore, the transmission probability of TF, the transmission probabilities of DL and UL MU transmissions, and the failed transmission probabilities of DL and UL MU transmissions can be solved by using an iterative numerical search method [14].

Let $P_{S,T}$, $P_{S,D}$, and $P_{S,U}$ be the successful transmission probabilities, and D_T , D_D , and D_U be the corresponding payload durations. In addition, $P_{B,T}$, $P_{B,D}$, and $P_{B,U}$ are the probabilities of the busy state owing to the transmission for TF, DL MU transmission, and UL MU transmission, respectively. The normalized successful transmission time duration (i.e., MAC layer throughput) for TF, DL MU, and UL MU transmissions is given by

$$S_T = P_{S,T} (1 - P_{B,D}) (1 - P_{B,U}) D_T / t_{avg}, \tag{14}$$

$$S_D = P_{S,D} (1 - P_{B,U}) (1 - P_{B,T}) D_D W_{0,D} / (W_{0,D} - 1) / t_{avg}, \tag{15}$$

$$S_U = P_{S,U} (1 - P_{B,D}) (1 - P_{B,T}) D_U W_{0,U} / (W_{0,U} - 1) / t_{avg}, \tag{16}$$

where t_{avg} is the average time duration spent when a packet is sent successfully [21]. The t_{avg} is given by

$$\begin{aligned}
 t_{avg} = & (1 - P_{B,D})(1 - P_{B,U})(1 - P_{B,T})\delta_I \\
 & + P_{S,D}(1 - P_{B,U})(1 - P_{B,T})(\delta_I + (t_{b,D}W_{0,D}/W_{0,D} - 1)) \\
 & + P_{S,U}(1 - P_{B,D})(1 - P_{B,T})(\delta_I + (t_{b,U}W_{0,U}/W_{0,U} - 1)) \\
 & + P_{S,T}(1 - P_{B,D})(1 - P_{B,U})t_{b,T} \\
 & + P_{C,MU}(1 - P_{B,T})t_{c,MU} \\
 & + P_{C,TF}(1 - P_{B,D})t_{c,T} + P_{C,TM}t_{c,TM}.
 \end{aligned} \tag{17}$$

In (17), $t_{b,T}$, $t_{b,D}$, and $t_{b,U}$ are durations of the channel’s busy state caused by successful transmission, and $t_{c,T}$, $t_{c,D}$, and $t_{c,U}$ are the durations of the channel busy condition caused by collision, respectively. In addition, $t_{c,MU} = \max(t_{c,D}, t_{c,U})$ and $t_{c,TM} = \max(t_{c,T}, t_{c,MU})$. Furthermore, we can derive the successful transmission probabilities and transmission probabilities (i.e., busy state) for TF, DL MU, and UL MU transmissions, respectively, as indicated below,

$$P_{S,T} = n_t \tau_T (1 - \tau_T)^{n_t - 1}, \tag{18}$$

$$P_{S,D} = n_d \tau_D (1 - \tau_D)^{n_d - 1}, \tag{19}$$

$$P_{S,U} = n_u \tau_U (1 - \tau_U)^{n_u - 1}, \tag{20}$$

$$P_{T,T} = 1 - (1 - \tau_T)^{n_t}, \tag{21}$$

$$P_{T,D} = 1 - (1 - \tau_D)^{n_d}, \tag{22}$$

$$P_{T,U} = 1 - (1 - \tau_U)^{n_u}. \tag{23}$$

The $P_{C,MU}$, $P_{C,TF}$, and $P_{C,TM}$ refer to collisional probabilities on the MU transmissions (such as UL MU and DL MU transmissions on the STA side), DL transmission for the TF on the AP side, and TF and MU transmissions on AP and STAs sides, respectively:

$$P_{C,MU} = P_{B,MU} - P_{S,MU}, \tag{24}$$

$$P_{C,TF} = P_{B,T} - P_{S,T}, \tag{25}$$

$$P_{C,TM} = P_{B,MU} P_{B,T}, \tag{26}$$

where $P_{B,MU} = 1 - (1 - \tau_D)^{n_D} (1 - \tau_U)^{n_U}$ and $P_{S,MU} = P_{S,D}(1 - P_{B,U}) + P_{S,U}(1 - P_{B,D}) = n_D \tau_D (1 - \tau_D)^{n_D - 1} (1 - \tau_U)^{n_U} + n_U \tau_U (1 - \tau_U)^{n_U - 1} (1 - \tau_D)^{n_D}$. By substituting (18)–(26) into (14)–(16), the average throughput of MU transmissions and TF transmission can be evaluated. To derive the sum throughput of transmissions, the channel access probability of the transmission type i ($i = 1, 2, \dots, N$) should be considered by

$$\tau_i = q_i(P_{F,i}, W_i, B_i), \tag{27}$$

where W_i and B_i are the initial CW size and maximum back-off stage of type i , respectively, and q_i is the mapping function based on the MAC scheme of type i (i.e., τ_i for the transmission probabilities of an AP or STA). The sum throughput of transmission type i is derived as

$$\begin{aligned}
 S_i = & P_{S,i} \prod_{b=1, b \neq i}^N (1 - P_{B,b}) t_{b,i} / t_{avg} \\
 = & n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{b=1, b \neq i}^N (1 - \tau_b)^{n_b} t_{b,i} / t_{avg},
 \end{aligned} \tag{28}$$

where t_{avg} is the average duration spent for each transmission type to send one payload successfully.

4 System efficiency by channel access mechanism of the TF

According to the IEEE 802.11ax standard, the TF that the AP transmits can use any AC [11]. Therefore, this does not reflect the environment of the wireless system, but allows the AP vendors to self-configure the AC of the AP with the highest priority. In this case, the AP will always be able to send the TF over a fixed highest priority AC. If the TF—which is in competition with the STA that performs the UL transmission—has a high priority, then the STA will have a low priority in the channel competition (i.e., random access).

As shown in Figure 5, if the TF transmitted by the AP has a fixed high-priority AC, then the UL traffic accessing the channel using random access will be pushed out owing to channel competition. The reason for defining the random access transmission in IEEE 802.11ax is that the STA can transmit the data of the system element when it is necessary to send an urgent message, or to change the receive operating mode for power saving. In this case, however, the AP always takes precedence over the TF or MU data transmission only when the priority is high. There are two main reasons for this problem. First, for a frame such as the abovementioned operating mode indication (OMI) frame or buffer status report (BSR), as the frame size is not large enough to allocate an RU from the TF and transmit MU with other traffic, the use of an empty channel space may reduce waste in the overall system. Second, when an STA has an association with an AP, the STA can be transmitted by the RU that the TF allocates to ensure its own data transmission. However, it cannot receive the TF for the STA that is not associated with the AP. To do this, the STA has to transmit its UL data through channel competition.

To solve this problem, we propose a channel access mechanism to determine the AC of the TF based on the BSR transmitted by the STA. The STA delivers BSRs to assist its AP

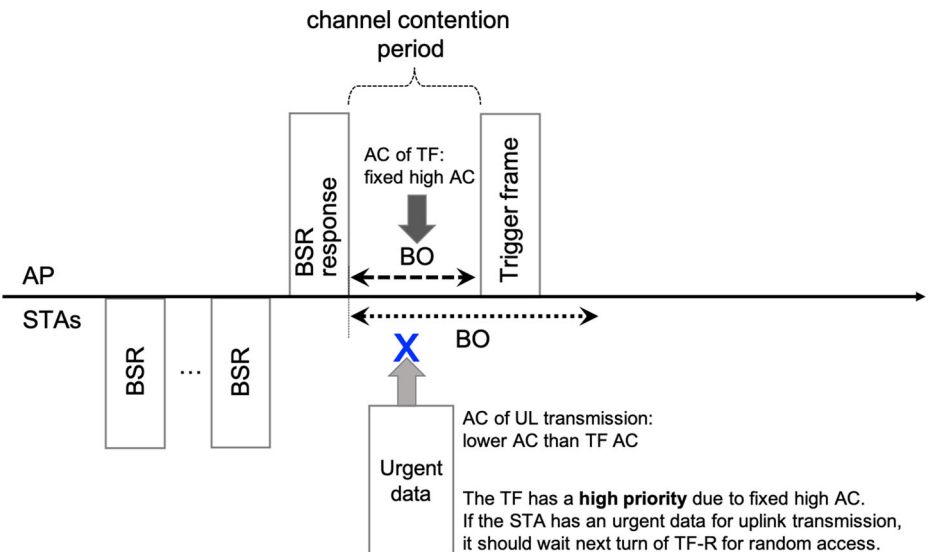


Figure 5 Channel competition with a fixed high-priority AC of an AP

in allocating UL MU resources. The STA can either implicitly deliver BSRs in the QoS control field or BSR control subfield of any frame transmitted to the AP (unsolicited BSR), or explicitly deliver BSRs in any frame sent to the AP in response to a BSRP TF (solicited BSR). The format of the control information subfield for BSR Control is shown in Figure 6. Specifically, the AC identifier (ACI) bitmap subfield indicates the ACs for which the buffer status is reported. Its encoding is shown in Figure 7. Each bit of the ACI bitmap subfield is set to unity to indicate the buffer status of the corresponding AC, and is set to zero otherwise. The size of the queue’s subfield is an 8-bit field that indicates the amount of buffered traffic for the STAs which send this frame. The STA uses the queue size subfield to indicate the amount of buffered traffic intended for the STA identified by the receiver address of the frame containing the QoS control field. The queue size subfield is present in the QoS data and QoS null frames sent by STAs with the 4th bit of the QoS Control field being equal to unity. The AP normally uses information contained in the queue size subfield to determine the transmission opportunity duration assigned to the STA or to determine the UL resources assigned to the STAs for the UL MU operation.

Each STA delivers its BSR information to the AP via several methods (e.g., TF-R, QoS control field, HE control field with ACK, and BSR polling) [11]. Through the received BSR information, the AP can determine the AC for the channel access rule of the TF for UL MU transmission of each STA. Based on the AC defined for UL MU transmissions, the AP stores the AC in the virtual UL MU queue. In this case, the virtual UL MU queue is defined for the classification and scheduling of the BSR information sent from each STA by each AC, rather than a physical queue of the AP. If several STAs have multiple ACs, the virtual UL MU queue internally determines the AC with the least back-off counter as the primary AC. In this study, the fastest accessible AC is applied to the TF. If several STAs have the same AC, there is only one AC in the UL virtual queue; thus the AC is determined as the primary AC. The AC of the TF determined by the virtual UL MU queue is defined as the primary AC so that the AP can include the TF in the DL queue of AP. Therefore, the AC of TF can be determined by applying the primary AC through the back-off counter rule in the UL virtual queue. That is, one of the four ACs in the UL virtual queue is defined as the primary AC by the EDCA back-off counter. Figure 8 shows an example of a virtual UL MU queue when the AC [VI] reaches a zero back-off counter. It is then selected as the primary AC of TF and assigned to the DL queue for the TF. The primary AC is then placed in the DL queue of AP, which has two methods: 1) placing the TF directly on the data accumulated in the DL queue, and 2) placing the TF in front of the DL queue regardless of the accumulated data. Figure 8 depicts the second method and applies this method in the simulation results of this study.

Figure 9 shows that the TF does not always have a high-priority AC for channel competition; instead, it determines the AC of the TF based on the BSR information as the proposed mechanism. The BSR information informs the STA that it wants to transmit UL data. An AP receiving this BSR information as a BSR frame can allocate a virtual UL MU queue according to the queue information of the STAs and transmit the TF according to the AC of UL MU data. With this proposed mechanism, it is possible to have a high-priority AC

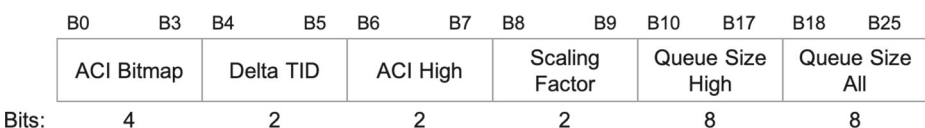


Figure 6 Control information subfield for buffer status report control

B0	B1	B2	B3
AC_BE	AC_BK	AC_VI	AC_VO

Figure 7 AC identifier (ACI) bitmap subfield encoding

or a low-priority AC at times, and the channel access becomes fair in terms of the channel competition.

5 Evaluation results

In this section, we analyze the simulation results for the coexistence of three types of transmissions, such as DL transmission for the TF, DL MU transmission for DL data, and UL MU transmission for UL data. For the simulation model, a system-level simulation model is constructed based on C++ programming, and the analytic model is derived with the use of MATLAB [18, 19]. We implement a computer program based on a modified DCF MAC algorithm given in [21], and the TF definition described in Figure 2 [11]. In our simulation, we defined three events: channel idle, successful transmission, and collision. Based on

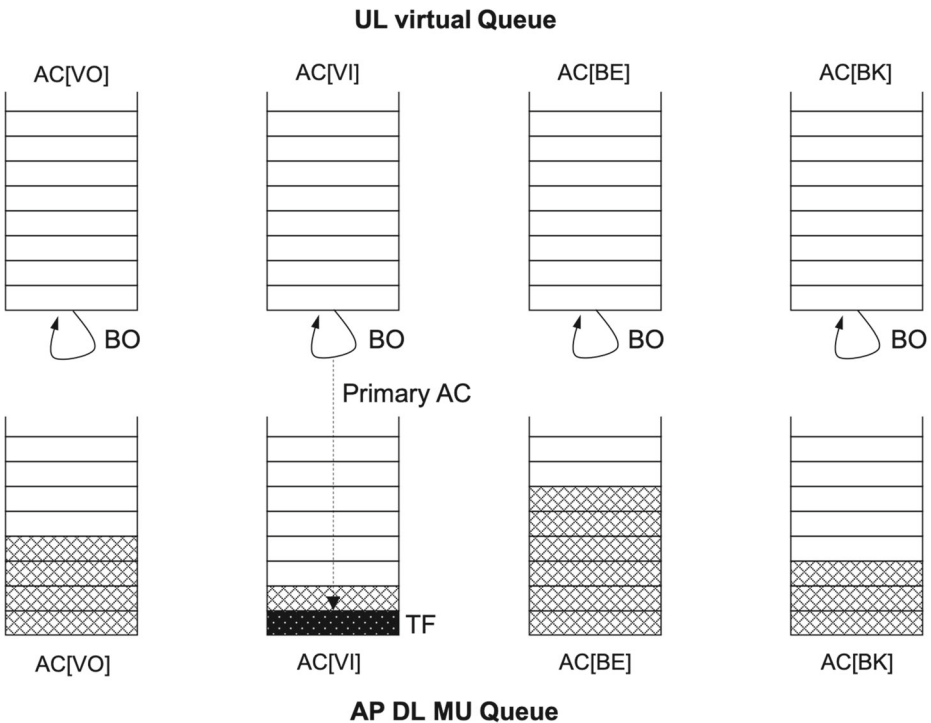


Figure 8 Example of virtual UL MU queue

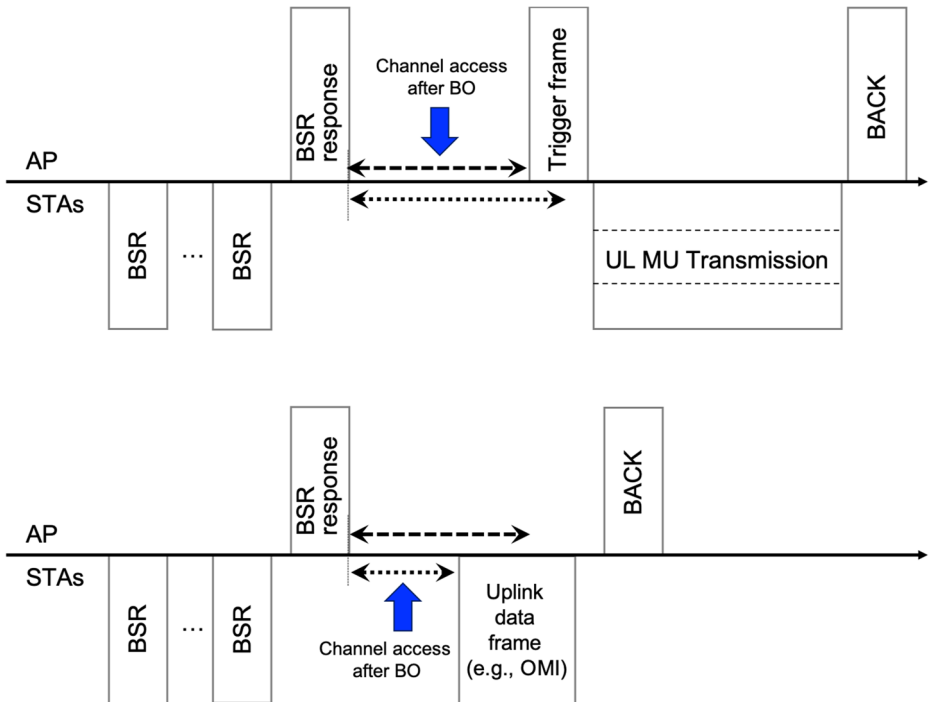


Figure 9 Deterministic AC of the TF based on the BSR

the accumulated numbers of events, the statistics of time-efficiency throughput, the channel access, and collision probability were computed for each STA.

The parameters used for analysis and simulation are listed in Table 1 [11, 14]. We assumed a saturated traffic that at a 100 Mbps channel bit rate (CBR) for all STAs. We studied the effects of basic access and RTS/CTS schemes for the WLANs, and assumed channel sensing to be idle (i.e., no hidden node problem, no false alarm, and missed detection).

Table 1 Wireless local area network simulation parameters

Parameter	Value
Packet payload duration	1ms
MAC and PHY layer headers	272 and 128 bits
T_{SIFS}	16 μ s
T_{DIFS}	34 μ s
Idle slot duration	9 μ s
Downlink initial CW size	16
Uplink initial CW size	32
Downlink cutoff stage	8
Uplink cutoff stage	8
TF length	28 bytes + 5 bytes \times num.user info + padding
MCS of TF	MCS 0 (BPSK, 1/2)

The TF length is dependent on the number of user information fields (e.g., four user information: 28 bytes + (5 bytes × 4) + 0 = 48 bytes or nine user information: 28 bytes + (5 bytes × 9) + 3 = 76 bytes) [11]. We randomly generated 20 APs and more than 400 STAs with the uniform distribution for the simulation of IEEE 802.11ax based on a dense environment. APs could transmit TFs and DL data to the negotiated STAs. To transmit UL data, STAs first informed their queue information through the BSR frame and, when their RU was allocated to the TF, received from the AP. Basically, STAs are configured to receive DL data from the AP.

We studied the effect of the maximum back-off stage setup of DL transmission for the TF. The maximum back-off stage increased from zero to eight with the RTS/CTS access. We set the DL transmission from the AP at a higher priority to access the channel compared with the UL transmission from the STAs (i.e., $W_U = 5W_D$). The results on the MAC throughput and transmission probabilities are presented in Figures 10 and 11, respectively. The analytical and simulation results are in close agreement. In Figures 10 and 11, the results show that when the maximum back-off stage increases, each DL transmission for the TF decreases its own throughput and transmission probability. Otherwise, the overall throughput (i.e., summation of DL transmission for the TF, DL transmission of DL data, and UL transmission of UL data) increases.

Figure 10 shows that the MAC throughput increases as the number of TFs increases with the RTS/CTS operation. As the number of TFs increased, the UL MU transmission increased and DL MU transmission decreased. In addition, it can be observed that the throughput for the UL MU transmission rate increased by the allocated RU by the TF for the UL MU transmission. As the number of TFs increased, the overall throughput tended to increase. This is attributed to the increased traffic that successfully performed UL MU transmissions using the TF.

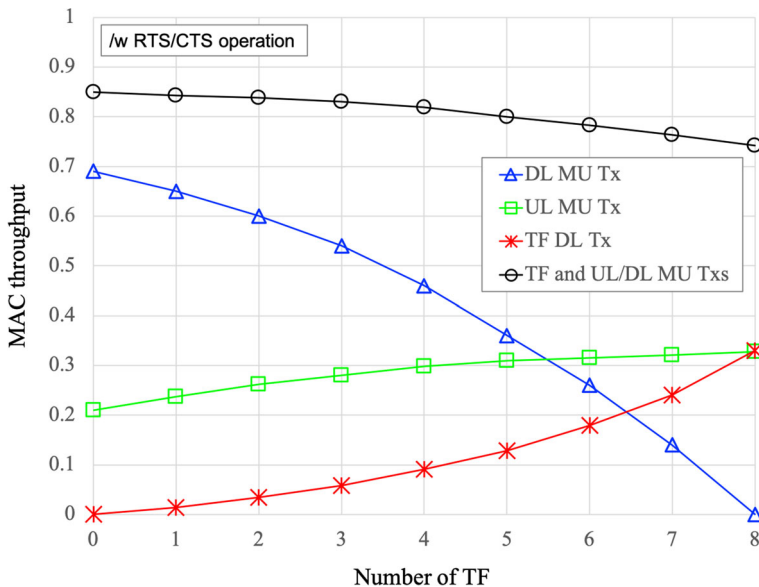


Figure 10 MAC throughput of TF and UL/DL MU transmissions when the number of TF increased with RTS/CTS operation

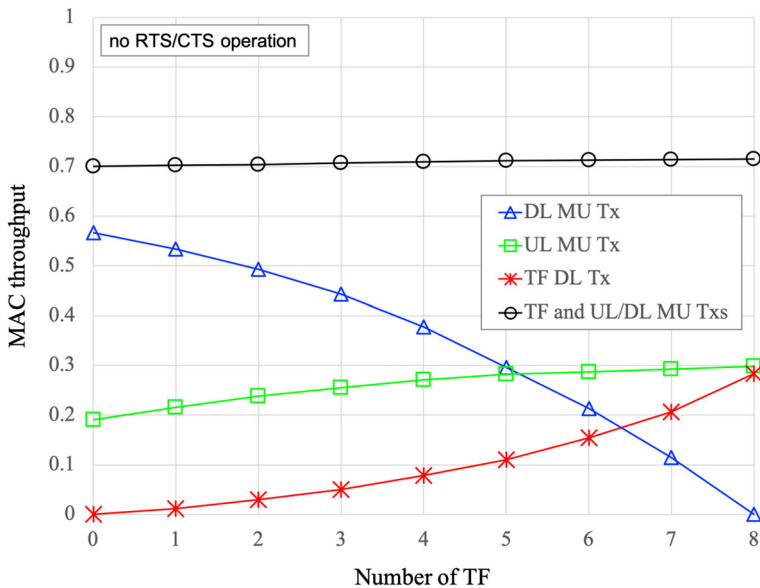


Figure 11 MAC throughput of TF and UL/DL MU transmissions when the number of STAs increased without RTS/CTS operations

Figure 11 shows that the MAC throughput increases as the number of TFs increases without the RTS/CTS operations. As the number of TFs increased, the UL MU transmission increased and the DL MU transmission decreased. In addition, the throughput for the UL MU transmission rate was increased by the allocated RU by the TF for the UL MU transmission. As the number of TFs increased, the overall throughput tended to increase. This is attributed to the increased traffic that successfully performed UL MU transmissions with the use of the TF. As the number of TFs increased from zero to eight, the MAC throughput of three types of transmissions increased from 70% to 72% without the RTS/CTS operation (constructive coexistence), but decreased from 87% to 74% with the RTS/CTS operation (nonconstructive coexistence). This demonstrates that the coexistence results critically depend on whether the 802.11ax system has low efficiency (e.g., 70% without RTS/CTS access) or high efficiency (88% with RTS/CTS access).

Figure 12 shows that the MAC throughput increases as the number of STAs increases. As the number of STAs increased, the throughputs of the UL MU transmission and DL MU transmission increased. In terms of throughput, the throughput of the DL MU transmission was higher. This is because the throughput of the TF rate decreased as the number of STAs increased. Moreover, we showed that the throughput increased as the number of STAs increased.

Figure 13 shows a comparison of the fairness for the case in which the TF does not define the AC and the case where the AC is adaptively set according to the BSR information. In the case of non-AC, the fairness index value is examined when AC is set to highest priority (for example, AC [VO]) or lowest priority (for example, AC [BE]) only. As the amount of traffic increased, the fairness decreased across the system. In the proposed scheme, when the AC of the TF was changed adaptively according to the queue information (for example, transmission of the BSR frame) sent from the STAs, the fairness index value of the overall

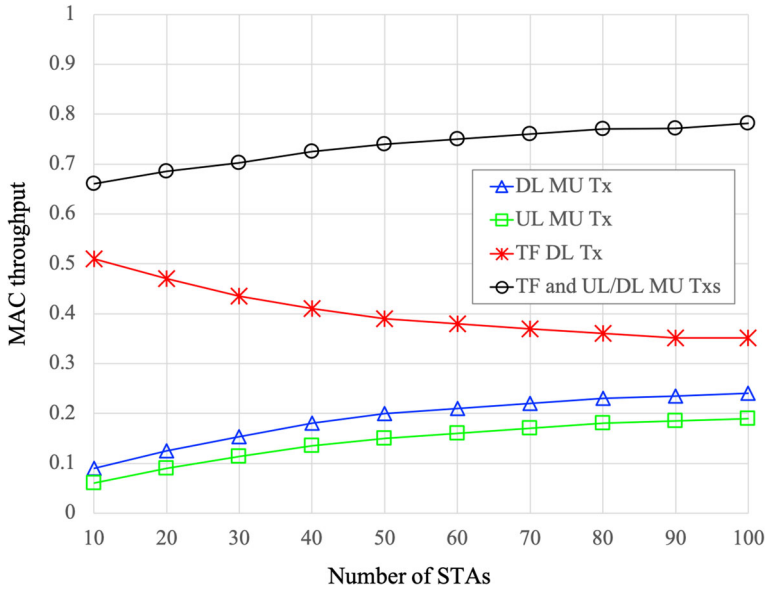


Figure 12 MAC throughput of TF and UL/DL MU transmissions when the number of STAs increase

system was compared with the fixed AC of the TF. As a result, it was observed that the overall fairness index value increased as the amount of traffic increased. This is because, in the case of many UL MU transmissions, the channel occupancy and transmission for the TF would be appropriate.

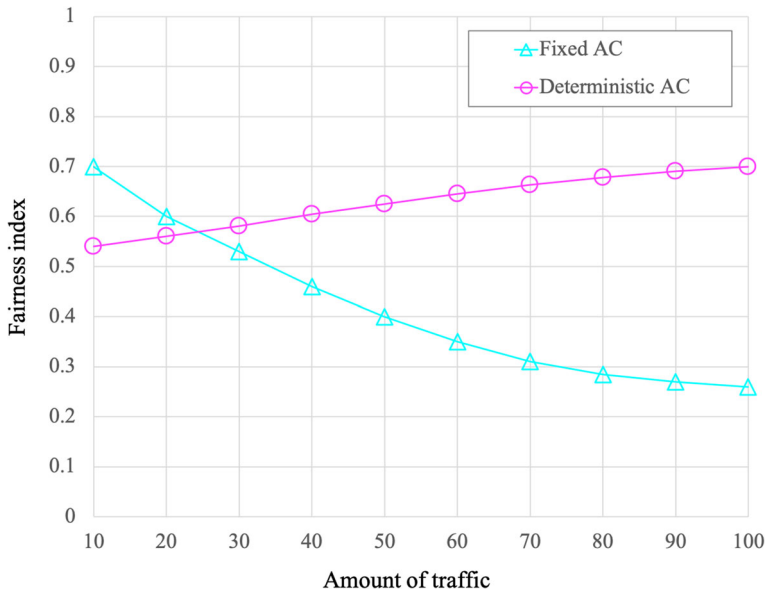


Figure 13 Fairness index when the amount of traffic increases

6 Conclusion

In this study, the DL transmission for the TF, the DL MU transmission for the DL data from the AP, and the UL MU transmission for the UL data from the STA are divided into three periods to analyze the MAC-level performance. The reason is that the TF transmitted by the AP is a control frame, unlike the data frame, and did not receive the ACK frame as a response. It is transmitted separately for DL MU transmissions. We analyzed the DL transmissions for the TF separately when three transmissions coexisted, such as DCT, DDT, and UDT. The results in terms of transmission probability, collision probability, and overall throughput are derived mathematically. In addition, we confirmed the results of the overall throughput and fairness index value when the TF had a fixed AC. By considering the BSR information about the virtual UL MU queue sent by the STA and determining the AC of TF according to the internal queue situation, the experimental results confirmed that the fairness index value increased. In this study, we considered the TF sent by the AP to be an important control frame for the UL MU transmission, and the analytical result was derived according to the strict separation of the transmission section. We also defined the AC so that the TF could be transmitted according to the queue information as the BSR information, thereby, raising the fairness index value of the system as a whole. In future work, our plan is to extend and optimize the DL transmission for the TF based on the target wake time (TWT) operation and the power saving mode with operating mode changes so that we can 1) reduce the waste time of channel contention, 2) increase performance to a system level simulation, and 3) support various analyses of large wireless environments.

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