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PAPER

# A Novel Low-Overhead Channel Sounding Protocol for Downlink Multi-User MIMO in IEEE 802.11ax WLAN

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**SUMMARY** The next generation wireless LAN standard IEEE 802.11ax aims to provide improved throughput performance in dense environments. We have proposed an efficient channel sounding mechanism for DL-MU-MIMO that has been adopted as a new sounding protocol in the 802.11ax standard. In this paper, we evaluate the overhead reduction in the 802.11ax sounding protocol compared with the 802.11ac sounding protocol. Sounding is frequently performed to obtain accurate channel information from the associated stations in order to improve overall system throughput. However, there is a trade-off between accurate channel information and the overhead incurred due to frequent sounding. Therefore, the sounding interval is an important factor that determines system throughput in DL-MU-MIMO transmission. We also evaluate the effect of sounding interval on the system throughput performance using both sounding protocols and provide a comparative analysis of the performance improvement.

***key words:*** *channel sounding protocol, DL-MU-MIMO, IEEE 802.11ax, wireless LANs*

## 1. Introduction

In recent years, there is an enormous increase in the usage of wireless LANs in a variety of dense environments such as homes, offices, cafes and airports. The use of wireless LAN employed with CSMA/CA as a Media Access Control (MAC) protocol in a dense environment causes substantial decline of the transmission opportunity or increase in packet collisions, thereby lowering the overall throughput. The standardization activities of the next generation wireless LAN (IEEE 802.11ax) started its Task Group (TG) in May 2014 to increase the system throughput in dense environments [1], [2]. The first draft standard was released in November 2016 [3] and on-going technical discussions continue in order to develop a final specification document by 2019. We have also been actively involved in the IEEE 802.11ax standardization activities since the launch of the TG.

In the conventional standard IEEE 802.11ac [4], the aim was to improve the maximum link throughput, whereas the IEEE 802.11ax standard aims to improve the overall average area throughput. Specifically, when compared with the conventional standard, the target of 11ax is the improvement of average per-station through-put to at least four times in dense environments [1], [2]. Therefore, the main technologies considered in 802.11ax are expected to increase the system capacity. These include Uplink Multi-User MIMO (UL-MU-MIMO), Downlink/Uplink Orthogonal Frequency Division Multiple Access (DL/UL-OFDMA) and Spatial Reuse (SR) that enables a plurality of access points (AP) and/or the stations to perform data transmission and reception simultaneously [3].

Downlink Multi-User MIMO (DL-MU-MIMO) mechanism has already been adopted in the 802.11ac standard including the channel sounding protocol to obtain the channel information required for pre-coding in DL-MU-MIMO transmissions [4]. While it is necessary to perform frequent sounding to obtain the time varying channel information accurately for pre-coding, this action increases the protocol overhead. Therefore, a compromise between precise channel knowledge at the AP and overhead reduction is needed, and the sounding interval is an important factor in enhancing the system throughput of DL-MU-MIMO transmission. However, there is no default value defined in the standard. The impact of sounding interval on the throughput performance using the 802.11ac sounding protocol has been reported [5]–[8].

In order to improve the system throughput, IEEE 802.11ax is considering new methods to enhance the existing sounding protocol in 802.11ac. We have proposed a channel sounding protocol for 802.11ax [9]. The proposed method aims to reduce the protocol overhead by utilizing an uplink multiplexing technique to feedback the channel state information framed from each station to AP replacing the sequential approach of 802.11ac sounding. The standardization meeting held in September 2015 adopted our proposal and related submissions from other organizations [10], as the 802.11ax sounding protocol [3]. In [11], [12], the authors demonstrate the effect of the 802.11ax sounding protocol using computer simulations. However, the results in [11], [12] are based on the preliminary phase of the IEEE 802.11ax standardization process and some of the evaluation parameters do not match the latest draft specification. Therefore, the efficacy of the 802.11ax sounding protocol has not been revealed using the current parameters described in the draft. In this paper, we quantitatively evaluate the overhead reduction in the 802.11ax sounding protocol using the latest parameters compared with 802.11ac sounding protocol. In addition, we also evaluate the effect of the sounding interval on the throughput performance using the 802.11ax sounding protocol.

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The rest of this paper is organized as follows. Section 2 introduces the standardization trend of IEEE 802.11ax. Section 3 provides a detailed explanation of the 802.11ax sounding method for MU-MIMO. Section 4 shows the numerical results of the 802.11ax method. Finally, Sect. 5 concludes this paper.

## 2. Standardization Trend in IEEE 802.11ax WLAN

IEEE 802.11ax standard is under development to improve the area throughput in environments where the wireless LAN devices are densely concentrated. As a result, the 802.11ax standardization activities mainly focus on simultaneous transmission techniques. The following outlines a few of the key technologies that are currently under discussion in the 802.11ax standard [3].

In addition to the existing DL-MU-MIMO in 802.11ac, UL-MU-MIMO with AP-driven centralized access control by utilizing a newly defined Trigger frame is adopted in 802.11ax [13]. The Trigger frame indicates necessary information for orthogonal multiplexing of UL frames to each station. It is expected not only to improve the transmission efficiency, but also to reduce the packet collision probability in CSMA/CA, owing to the reduction in the number of simultaneous channel accesses by the stations multiplexed in UL-MU-MIMO [14].

UL-MU-MIMO in 802.11ax focuses not only on the multiplexing of UL data frames, but also the multiplexing of UL control frames and UL management frames. Therefore, as an extension of the DL-MU-MIMO in 802.11ac, the uplink multiplexing of certain response frames from each station such as Block ACK frames and Compressed Beamforming (CB) frames associated with sounding related to DL-MU-MIMO transmission has also been studied in 802.11ax [3]. In the Sect. 3, the agreement obtained by the authors' proposal at 802.11ax regarding the multiplexing of feedback frames associated with sounding protocol is described in detail.

OFDMA is a multiple user technology used even in LTE and WiMAX, where the OFDM subcarriers are grouped into Resource Units (RUs) in order to improve the frequency utilization efficiency by assigning good signal quality RUs to multiple users [15], [16]. In 802.11ax, it is possible to support simultaneous transmission of up to nine users in the 20MHz bandwidth using 1/4th of the sub-carrier spacing arranged with the conventional standards. In addition, OFDMA is applicable to both downlink (DL) and uplink (UL) in 802.11ax. Similar to UL-MU-MIMO, UL-OFDMA is enabled by the transmission of Trigger frame.

In a dense environment where the APs are placed close to each other, the signal received from the neighboring Basic Service Set (BSS) could cause excessive waiting due to the so-called exposed terminal problem, which leads to a decrease in overall throughput. Spatial Reuse is an adaptive technique for controlling the carrier sensing threshold value based on the transmission power or received interference level from other BSSs, thereby enabling transmissions that failed even in the conventional method. Accordingly, spatial frequency reuse between multiple BSSs is achieved and hence improved throughput performance can be expected [17]–[19].

802.11ax has discussed techniques that not only improve the area throughput but also the maximum link throughput, such as the application of 1024QAM as a modulation and coding scheme (MCS) level.

Thus, 802.11ax is expected to improve the system throughput at least four times in dense environments using the above techniques [20]–[23].

## 3. Channel Sounding Protocol for Multi-User MIMO

### 3.1 Channel Sounding Protocol in IEEE 802.11ac (Conventional Method)

Figure 1 illustrates the conventional sounding protocol for DL-MU-MIMO used in 802.11ac. An AP initiates the sounding protocol by transmitting a Null Data Packet (NDP) Announcement (NDPA) frame, specifying the target stations that are required to estimate the channel information. After a Short Inter Frame Space (SIFS) interval of 16$\mu$s, the AP sends an NDP frame containing only the physical header for channel estimation and each station notified in the NDPA frame estimates the downlink channel using the NDP frame. The first station specially indicated by the NDPA frame sends its CB frame including the estimated channel information at SIFS interval after receiving the NDP frame. All the other indicated stations wait for their Beamforming Report Poll (BRP) frames from the AP to feed back their CB frames. The CB frame format has been accepted as a sole feedback format for 802.11ac in order to reduce the total number of bits in the feedback frame, and is based on the orthonormal property of the beamforming matrix $V$ obtained by singular value decomposition (SVD) technique represented in the angle domain [24]–[26]. After receiving the CB frames from all the stations, AP can perform pre-coding for DL-MU-MIMO transmission using the channel information obtained from the CB frames and simultaneously transmit data frames to multiple stations.

Therefore, in the 802.11ac sounding protocol, the time required for sounding becomes larger as the number of sounding stations increase, since the CB frames are fed back sequentially from each station. This leads to increase in overhead, associated with the sounding protocol, with the number of sounding stations.

### 3.2 Channel Sounding Protocol in IEEE 802.11ax (Proposed Method)

The 802.11ax sounding protocol proposed by the authors and agreed at the IEEE 802 September 2015 meeting is shown in Fig. 2. As shown in Fig. 2, the CB frames from stations are simultaneously fed back with UL multiplexing scheme in 802.11ax protocol in contrast to sequentially in 11ac sounding. UL multiplexing of CB frames can be either

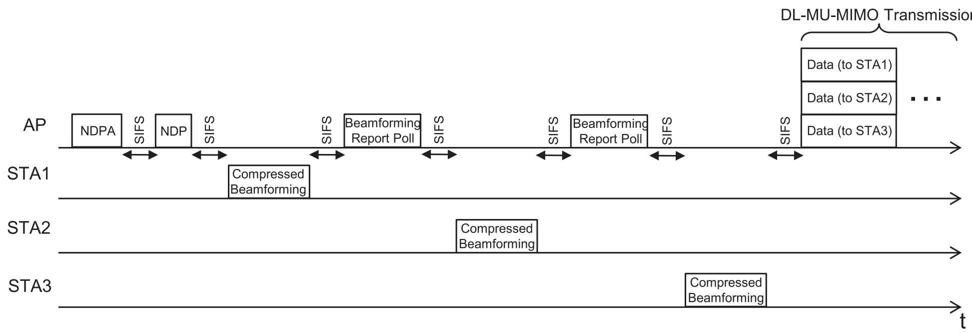


**Fig. 1** IEEE 802.11ac sounding protocol (Conventional method).

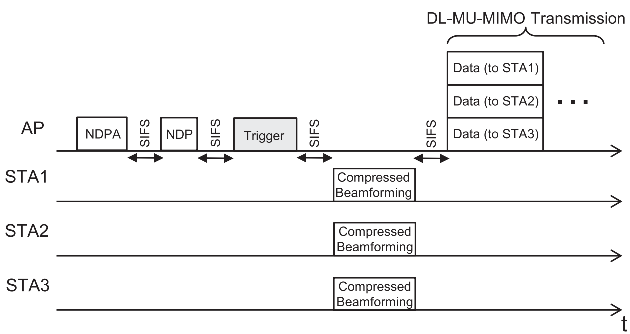


**Fig. 2** IEEE 802.11ax sounding protocol (Proposed method).

| Octets: | 2 | 2 | 6 | 6 | 8 | 6 | | 6 | | 4 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Frame Control | Duration | Receiver Address | Transmitter Address | Common Info | User Info | ··· | User Info | (Padding) | FCS |

**Fig. 3** Trigger frame format for sounding.

UL-MU-MIMO or UL-OFDMA.

In addition, a Trigger frame, which is a control frame, is broadcast to the stations SIFS interval after NDP frame in order to notify necessary information for orthogonal multiplexing of CB frames in UL. Figure 3 illustrates the Trigger frame format. Trigger frame contains common information for all stations such as Physical layer Protocol Data Unit (PPDU) length and Physical header information of the UL frame that is the response to the Trigger frame in the Common Info field, and specific individual information for each station such as resource allocation information, MCS etc. in the User Info fields.

It can be inferred that, by multiplexing the CB frames in UL using the Trigger frame, the time required for channel sounding in the 802.11ax sounding protocol is possibly reduced when compared with the 11ac sounding protocol. In DL-MU-MIMO transmission, since the time required for sounding is an overhead that impairs the throughput improvement, the 802.11ax sounding can be expected to further improve the throughput performance of DL-MU-MIMO transmission. In particular, while the time required for sounding increases with the number of sounding stations in 11ac, 11ax sounding can be realized at a substantially constant amount of time regardless of the number of stations sounded which is limited by the maximum possible UL multiplexing number. Therefore, the advantage of throughput improvement in DL-MU-MIMO using 802.11ax sounding protocol is expected to become larger with the number of sounding stations as compared with 802.11ac sounding.

In Sect. 4, the overhead reduction of the proposed sounding in 802.11ax is quantitatively evaluated using computer simulations.

## 4. Numerical Results

### 4.1 System Parameters

Table 1 shows the main simulation parameters used for the computer simulations. In this paper, the UL multiplexing method for the CB frame is assumed to be UL-MU-MIMO. In general, carrier frequency offset (CFO), timing offset and the difference between multiple stations' received signal strength at AP cause the SNR degradation in UL-MU transmission. 802.11ax guarantees to keep those factors within 350 Hz, ±0.4 $\mu$s and ±3 dB using the Trigger frame exchange, respectively. The authors in [27] show that 802.11ax can nearly ignore the degradation due to CFO. Moreover, if there is enough dynamic range in the A/D converter, the adverse impact of received signal power difference can be also ignored [28], [29]. Therefore, in this paper, we assume that there is no deterioration due to the degradation factors including the timing offset which is within the Guard Interval. In addition, the crosstalk between stations is also a degrading factor in UL-MU-MIMO and it depends on the MIMO decoding method. We assume Zero-Forcing method as a MIMO decoding method in this paper. If the packet error of the CB frames occurs, the AP repeats the sounding to the error stations until all CB frames are received correctly.

As shown in Fig. 3, the Trigger frame size depends on the number of sounding stations $n$, as 28+6$n$ bytes. The CB frame size depends on the channel feedback information amount which is determined uniquely by some parameters such as the number of antenna elements, the bandwidth, codebook size and the sub-carrier grouping number ($N_g$). For a fair comparison in terms of the CB frame size, we assume that $N_g$=4 for 802.11ax as the number of sub-carriers in 802.11ax is four times as that of 802.11ac. Moreover, for 11ax we assume the AP applies a linear interpolation scheme to estimate the CSI for the sub-carriers with no CB

**Table 1** System parameters.

| | |
|---|---|
| Bandwidth | 20M Hz |
| Channel Model | TGac Model-D (Doppler Frequency=0.4Hz) |
| Traffic | Full Buffered |
| Data Frame Size | 1500 byte |
| Frame Aggregation | A-MPDU (2 MPDUs) |
| Data MCS | Based on SINR (Target PER=10%) |
| 11ac OFDM symbol length | 4 us (3.2us data length + 0.8us GI) |
| 11ax OFDM symbol length | 16 us (12.8us data length + 3.2us GI) |
| HE_LTF symbol length | 16 us (4x HE_LTF + 3.2us GI) |
| FEC | BCC |
| NDPA Frame Size | 21+4*n* byte (*n*: Number of Sounding STAs) |
| Trigger Frame Size | 28+6*n* byte |
| BF Report Poll Frame Size | 21 byte |
| Control/Management Frame MCS | MCS0 (BPSK, r=1/2) |
| DIFS | 34 us |
| SIFS | 16 us |
| Slot Time | 9 us |
| $CW_{min}$ | 15 |
| UL-MU Method | UL-MU-MIMO |
| Carrier Frequency Offset in UL-MU | 350 Hz |
| Timing Offset in UL-MU | ±0.4 us |
| Power Difference in UL-MU | ±3 dB |
| Number of spatially multiplexed users | Up to 8 |
| Number of Antenna Elements | UP to 8 (AP)<br>1 (STA) |
| Subcarrier Grouping ($N_g$) | 1 (in case of 11ac sounding)<br>4 (in case of 11ax sounding) |
| Codebook Size | 5bits for Ψ, 7bits for Φ (Codebook Information=0) |
| Pre-coding Method | Zero-Forcing |
| MIMO Decoding Method | Zero-Forcing |
| Scheduling for DL-MU-MIMO | Random Selection |

information in the CB frame.

802.11ac operates with an OFDM Symbol length of 4$\mu$s and 64 points FFT, as opposed to 16$\mu$s and 256 points FFT in 11ax, respectively. Each frame in the sounding protocol is assumed to be transmitted with a fixed MCS0. On the other hand, the MCS of the data frames transmitted using DL-MU-MIMO, is assumed to be at the maximum permissible MCS level at the instant where there is less than 10% packet error rate according to the SINR. The AP, based on the CSMA/CA mechanism, continuously transmits data frames using DL-MU-MIMO until the next sounding interval.

In the 802.11ax standardization, the calibration of the simulation results had been performed step-by-step among some companies and organizations for the validity of each simulator. The validity of our simulator is basically guaranteed by these calibration tests [30]–[33].

### 4.2 Time Required for Sounding Protocol

Firstly, we evaluate the time required per sounding sequence in 802.11ac and 802.11ax, which influences the throughput performance for DL-MU-MIMO. In this paper, the time is defined as the duration from the start of the NDPA frame transmission to the end of reception of the CB frames from all the stations sounded by the NDPA frame. Therefore, the time required for sounding in 802.11ac and 802.11ax can be expressed as

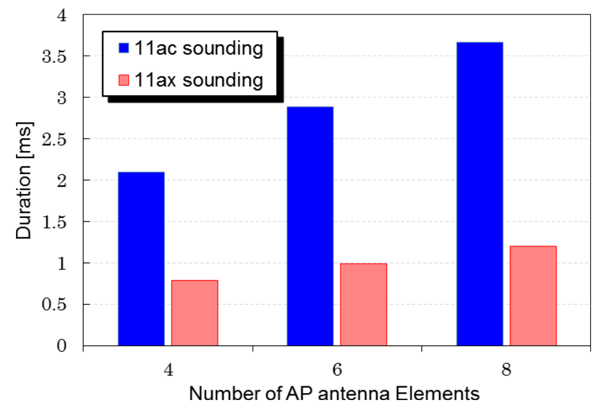


**Fig. 4** Time required per sounding sequence (for 4 sounding stations).

$$T_{11ac}(n) = T_{B.O.} + T_{DIFS} + T_{NDPA}(n) + T_{NDP} + n \times T_{CB} + (n-1) \times T_{BRP} + 2n \times T_{SIFS} \quad (1)$$

$$T_{11ax}(n) = T_{B.O.} + T_{DIFS} + T_{NDPA}(n) + T_{NDP} + T_{Trigger}(n) + T_{CB} + 3 \times T_{SIFS} \quad (2)$$

where $n$ is the number of sounding stations, $T_{B.O.}$ is the average back-off duration, and $T_{DIFS}$ and $T_{SIFS}$ are DIFS time period and SIFS time period, respectively. $T_{NDPA}(n)$ and $T_{Trigger}(n)$ denote transmission times of the NDPA frame and Trigger frame in the case of $n$ sounding stations, respectively. In addition, $T_{NDP}$, $T_{CB}$ and $T_{BRP}$, which have fixed length regardless of $n$, are the transmission times of the NDP frame, CB frame and BRP frame respectively.

Therefore, the protocol gain, G, increases in the 11ax sounding protocol as follows,

$$\begin{aligned} G &= T_{11ac}(n) - T_{11ax}(n) \\ &= (n-1) \times (T_{CB} + T_{BRP}) + (2n-3) \\ &\quad \times T_{SIFS} - T_{Trigger}(n) \end{aligned} \quad (3)$$

Figure 4 shows the time required per sounding sequence when four stations are sounded for the number of AP antenna elements of 4, 6, and 8. As the number of antenna elements increase, the feedback channel information amount required increases thereby increasing the CB frame size. Therefore, it can be seen that although the sounding time required, both in 802.11ac and 802.11ax, increases with the number of antenna elements, the increase can be minimized by multiplexing the CB frames in 802.11ax sounding. As a result, compared to 11ac sounding, there is greater reduction in the duration of sounding as the number of antenna elements increase.

Figure 5 shows the time required for 11ac and 11ax sounding protocols when the number of sounded stations is varied, for a constant number of AP antenna elements, 8.

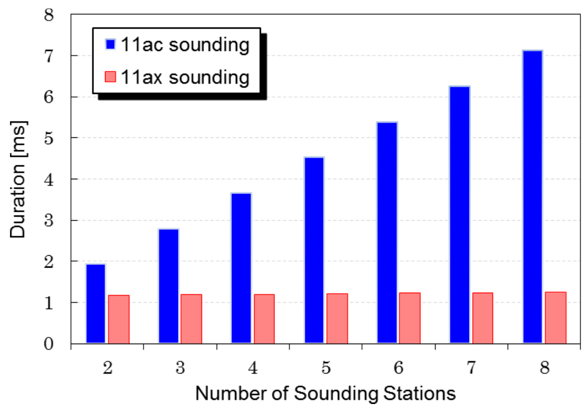


**Fig. 5** Time required per sounding sequence (for 8 AP antenna elements).

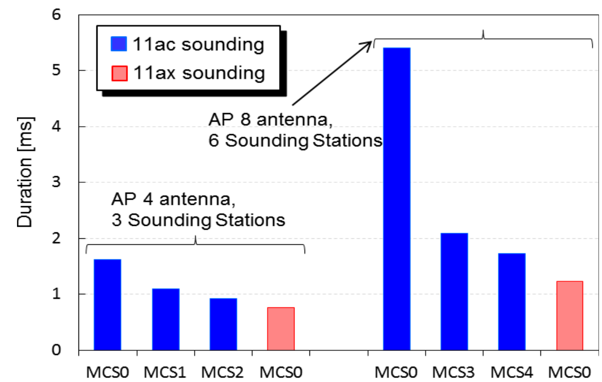


**Fig. 6** Time required per sounding sequence with high MCS for CB feedback in 11ac sounding.

As mentioned in Sect. 3.1, the CB frames from each station are sequentially fed back in the case of 11ac. As a result, as shown in Fig. 5, the time required for sounding increases proportionally with the number of sounding stations. On the other hand, in 11ax, owing to UL multiplexing of the CB frames, it is possible to respond the CB frames from all sounding stations in a constant time without depending on the number of stations. Although the total time required in 11ax sounding is not fixed due to the sizes of the NDPA frame and Trigger frame which increase slightly with the number of sounding stations, the sounding time can be achieved almost constant regardless of the number of stations in contrast to 11ac sounding. As a result, the time required for 11ax sounding is reduced by 39.4% for 2 stations, and by 82.4% for 8 stations compared to 11ac sounding, respectively.

In Fig. 4 and Fig. 5, the CB frame is assumed to be transmitted with MCS0. However, in the 11ac sounding protocol, though the AP cannot apply the UL-MU-MIMO scheme, the AP can utilize its own multiple antennas as a receive diversity method. As a result, the stations in 11ac can transmit the CB frames using higher MCS theoretically, which leads to reduction in the required time for sounding. The cumulative distribution function of the SNR, in the case of using Maximal Ratio Combining (MRC) as the diversity method, can be expressed as

$$F(\gamma) = 1 - \exp\left(-\frac{\gamma}{\Gamma}\right) \sum_{m=1}^{M} \frac{(\gamma/\Gamma)^{m-1}}{(m-1)!} \tag{4}$$

where $M$ is the number of antenna elements and $\Gamma$ is the averaged SNR of each antenna element. From Eq. (4), in general, higher MCSs up to MCS2 can be selected in case of 4 AP antennas, and up to MCS4 in case of 8 AP antennas due to the improvement in SNR, respectively. Therefore, Fig. 6 shows the time required per sounding sequence when applying high MCS UL transmission of CB feedback in 11ac sounding for 4 AP antennas with 3 sounding stations and 8 AP antennas with 6 sounding stations respectively. As shown in Fig. 6, even though the stations in 11ac can theoretically transmit the CB frame using high MCS with receive diversity at the AP, the 11ax sounding protocol has smaller overhead than the 11ac sounding protocol.

Furthermore, the selected MCS of the CB frame is determined by the transmitting stations and the AP cannot control the MCS. In practice, it is difficult for the stations to select the appropriate high-MCS since the stations cannot know apriori the presence/absence or the implementation method of the receive diversity, and the actual amount of SNR improvement at the AP. Therefore, in general, the stations often select MCS0 since the CB frame is a type of management frame regardless of SNR and the number of AP antenna elements. For these reasons, we assume that the MCS of the CB frame is fixed at MCS0, hereafter.

### 4.3 Throughput Performance

In 802.11ax, owing to the reduction in time required for the proposed sounding as described in Sect. 3.2, an improvement in the system throughput for DL-MU-MIMO transmission can be expected. This is because, in addition to the MAC overhead reduction in sounding time, the AP can start DL-MU-MIMO transmission with higher channel correlation in time-varying channels by the reduction of channel aging time, the time difference between NDP frame and DL-MU-MIMO data frame. In this section, we evaluate the effect of time reduction on the system throughput performance in the 11ax sounding protocol.

The sounding interval is also an important factor while assessing the system throughput. In terms of MAC overhead reduction, it is better to increase the sounding interval. However, an excessively large sounding interval will lead to lowering of the channel correlation from the timing of sounding to the actual timing of DL-MU-MIMO transmission due to channel aging, resulting in SINR degradation. There is a trade-off between the MAC overhead reduction and the deterioration of channel correlation due to channel aging with respect to the selection of sounding interval. Consequently, Fig. 7 shows the degradation in the average SINR characteristics in DL-MU-MIMO with channel aging time for AP antenna elements 4 and 8, and the number of multiplexed stations 3 and 6 respectively when the stations are randomly located at a concentric distance from the AP where

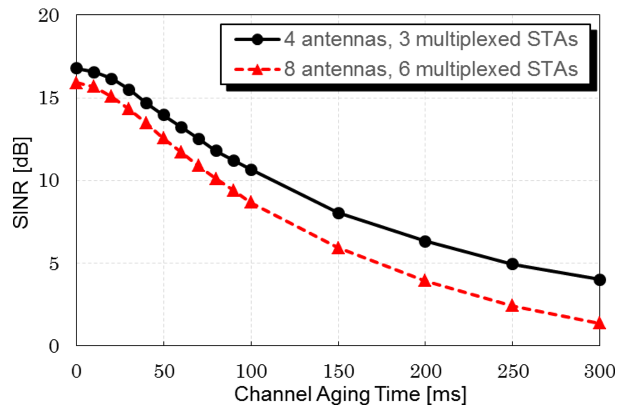


**Fig. 7** Average SINR in DL-MU-MIMO with channel fluctuation.

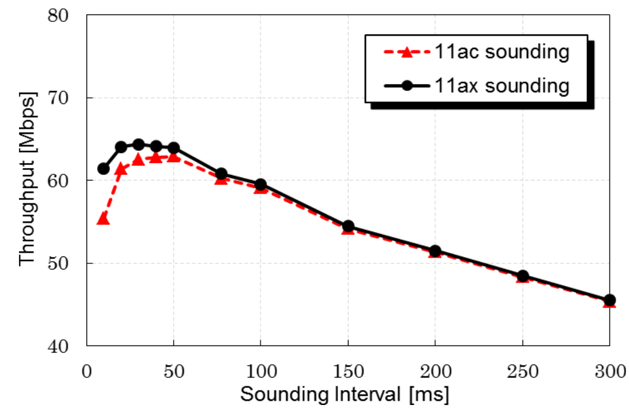


**Fig. 8** Average throughput versus sounding interval for 4 AP antennas with 3 multiplexed stations.

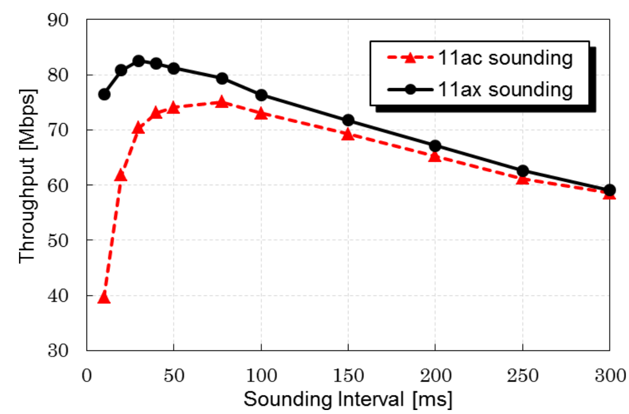


**Fig. 9** Average throughput versus sounding interval for 8 AP antennas with 6 multiplexed stations.

the SNR is 20dB. The propagation path model is a typical office environment in IEEE 802.11ac (Model_D) [34].

From the results of Fig. 7, it can be inferred that there is severe deterioration in SINR in both the cases as the channel aging time proceeds. Particularly, there is significant impact of inter-user interference and hence larger SINR degradation for large spatial multiplexing, 6. For example, in the case of 6 spatially multiplexed stations, at the channel aging time of 100 ms the amount of SINR degradation is 7.2 dB and it further deteriorates to 14.5 dB for 300 ms. This means that when the AP continues to utilize the same channel information obtained by sounding for the pre-coding in DL-MU-MIMO, it leads to applying non-optimal weights for DL-MU-MIMO due to channel aging. This results in an increased inter-user interference causing SINR degradation. Therefore, we require periodic sounding in order to obtain accurate channel information without affecting the MAC overhead.

Based on the results of Fig. 7, we further evaluate the effect of sounding interval on the throughput performance. Figure 8 and Fig. 9 show the throughput results when the sounding interval is varied for 4 AP antennas with 3 multiplexed users and 8 AP antennas with 6 multiplexed users respectively. As with the case in Fig. 7, the results in both Fig. 8 and Fig. 9 are the average throughput performance when the stations are randomly located at a concentric distance from the AP where the SNR is 20 dB.

The throughput characteristics have same behavior for both the cases where, the throughput improves and reaches a peak until a certain sounding interval and deteriorates thereafter. In other words, for each case, the sounding interval corresponding to the maximum peak throughput is the optimum sounding interval. These results are attributed to the trade-off between SINR degradation due to channel aging and the increased MAC overhead. When the sounding interval is smaller than the optimum value, there is excessive sounding that leads to decrease in throughput due to increased MAC protocol overhead. On the other hand, for a sounding interval larger than the optimum value, although the impact of the increased overhead is small, the effect of SINR degradation becomes dominant due to channel fluctuation, which leads to decrease in throughput. The optimum sounding interval for 11ax can be seen to shift towards the left side; i.e., a smaller sounding interval as compared to 11ac, due to the overhead reduction. For the three sounding stations case shown in Fig. 8, the optimal interval for 11ac sounding is 50 ms, whereas for 11ax it is 30 ms. Similarly, for the six sounding stations case in Fig. 9, the optimum interval is 30 ms for 11ax, shifted from 77.5 ms for 11ac. The results reveal that increasing the sounding frequency in 11ax will lead to very small throughput degradation compared to 11ac due to the overhead reduction in 11ax sounding.

The difference in maximum achievable throughput for 11ax over 11ac increases from 2.4% for three sounding stations (Fig. 8) to 10.0% for six sounding stations (Fig. 9). This is because the overhead reduction effect by multiplexing the CB frames is increased with the number of sounding stations.

In addition, with respect to the sounding interval, for a large sounding interval, the ratio of the sounding time to DL-MU-MIMO transmission time is relatively small. Hence, the throughput improvement for 11ax sounding, even when the number of sounding stations is large, is not significant. On the other hand, when the sounding interval is short, the relative proportion of the sounding time is increased and the sounding overhead becomes dominant. Therefore, the effect of reduction in overhead in 11ax sounding becomes relatively

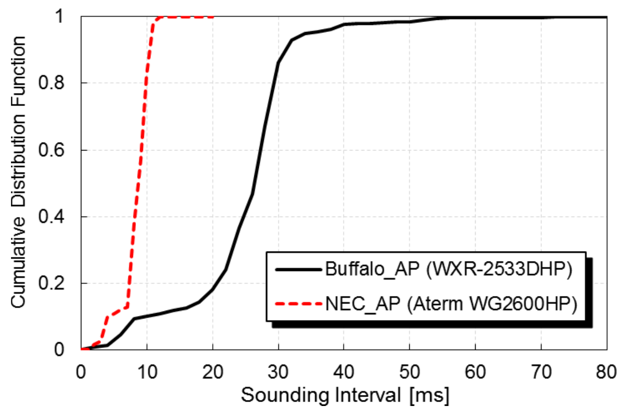


**Fig. 10** Example of results of sounding interval in existing 802.11ac products.

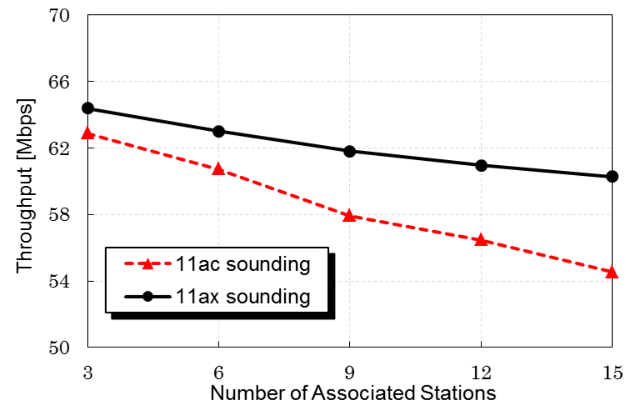


**Fig. 11** Maximum throughput versus the number of associated stations for 4 AP antennas with 3 multiplexed stations.

more and causes substantial throughput improvement as opposed to a large sounding interval. The advantage of 11ax sounding in throughput enhancement of DL-MU-MIMO is expected to become larger for shorter sounding intervals. In Fig. 9, for the case of six sounding stations, it is confirmed that the throughput improvement in 11ax is 93.1% at 10 ms interval and 17.4% at 30 ms interval respectively when compared with 11ac. In fact, our packet capture experiments show that some of the existing 802.11ac products support DL-MU-MIMO function with shorter sounding intervals less than 50 ms. Figure 10 shows the results of sounding interval obtained using the two products ([35], [36]) with 3 multiplexed stations for saturated DL traffic in a static environment of an office approximately 10 x 12 m in size. Three stations with one antenna element each are co-located around the AP with cell radius 2 m. The sounding interval is obtained by calculating the time difference between the reception timing of NDPA frames captured using Omipeek Professional, which is a WLAN packet capture tool. The results indicate that the sounding interval of WG2600HP and WXR-2533DHP are almost less than 10 ms and 30 ms respectively. Therefore, it can be inferred that the APs are often compelled to operate at shorter sounding intervals in actual environments since it is difficult for the APs to determine the optimal sounding interval in reality, contrary to the simulations which assume a certain channel model. Therefore, similar products with shorter sounding intervals are expected to significantly improve the system throughput using the 11ax sounding protocol compared with 11ac sounding protocol.

Results in Fig. 8 and Fig. 9 are evaluated for same number of sounding stations and spatial multiplexing number. However, in actual environments, it is common that the number of the associated stations with AP is larger than the spatial multiplexing number. In such cases, the AP needs to select a set of stations for DL-MU-MIMO from among all the associated stations using certain metrics such as the user correlation obtained by sounding. Therefore, we evaluate the throughput improvement by varying the number of associated stations for 4 AP antennas with 3 multiplexed stations. Figure 11 shows the maximum achievable throughput value when the number of associated stations is varied with random user scheduling method for simplicity. The scheduling method involves the AP randomly selecting sets of three stations regardless of their user correlations. Incidentally, in consideration of the possible number for multiplexed stations, the number of sounding stations per sequence is fixed at three as in Fig. 8. For example, 4 sounding sequences need to be carried out to receive the CB frames from a total of 12 associated stations. Figure 11 reveals a throughput improvement of 2.4% in case of 3 associated stations and it further improves to 10.5% for 15 stations. In 802.11ax, the number of associated stations is envisioned as usage scenes, the further improvement using 11ax sounding protocol can be expected in such environments.

## 5. Conclusions

We have proposed a sounding method for DL-MU-MIMO that will be adopted as a new sounding protocol in 802.11ax standard. In this paper, we evaluated the MAC overhead reduction of the 11ax sounding protocol and the impact of the sounding interval on the system throughput characteristics. Our simulation results show that the 11ax sounding protocol can significantly reduce the time required for sounding, and hence achieve an improvement in throughput for DL-MU-MIMO transmission by multiplexing the CB frame in UL as compared to the 802.11ac. In addition, it is also apparent that the improvement in throughput is larger with increasing number of stations and shorter sounding interval. IEEE 802.11ax, the next generation standard, is envisaged to solve the problems of the current wireless LAN standards that would cause a reduction in throughput under dense environments. Therefore, the 11ax sounding protocol is an effective approach to the problem.

In this paper, in order to fairly evaluate the throughput improvement obtained by UL multiplexing of the CB frames in 11ax sounding, the effect of multiplexing the Block ACK frames from multiple stations in UL is not included. In the future, we will comprehensively evaluate the throughput improvement in 11ax DL-MU-MIMO including the overhead reduction by UL multiplexing of Block ACK frames which is also agreed in 802.11ax standard.

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