Implementation and Evaluation of IEEE 802.11ax Channel Sounding Frame Exchange in ns-3

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ABSTRACT

To enable extremely high throughput in wireless local area networks (WLANs), new features including Multi-User Multiple-Input Multiple-Output (MU-MIMO), beamforming techniques, and coordinated beamforming among multiple access points (APs) have been considered in current and future standards. All of these features require stations to measure the wireless channel and feed back channel state information (CSI) to APs. However, it is still impractical to evaluate system-level performance of these techniques in ns-3 since the functionality of CSI acquisition is missing. In this paper, an ns-3 implementation of channel sounding process in medium access control (MAC) layer based on IEEE 802.11ax is described. Simulation results are presented to show the overhead of the channel sounding process and provide a first step toward evaluating the impact of channel sounding on network performance.

CCS CONCEPTS

• **Networks** → **Network simulations**.

KEYWORDS

ns-3, Wi-Fi, channel sounding, MU-MIMO

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1 INTRODUCTION

IEEE 802.11ax standard is a widely deployed standard in current wireless local area networks (WLANs). By incorporating Multi-User Multiple-Input Multiple-Output (MU-MIMO), the standard allows better throughput and efficiency by using multiple antennas on current access points (APs) to exploit degrees of spatial freedom [1, 3]. As the demands of data services explode, the IEEE 802.11 working group has begun development of a standard for extremely high throughput WLANs, which is IEEE 802.11be. The new standard will incorporate a new functionality of coordinated beamforming, which allows simultaneous MU-MIMO transmissions in multiple basic service sets (BSSs) and also eliminates inter-BSS interference [4]. Both techniques rely on channel state information (CSI) to manipulate beams and cancel interference [5, 6].

As a powerful network simulator to validate system-level performance, ns-3 provides partial support of 802.11ax features, but currently does not support MU-MIMO. Challenges to support MU-MIMO include incorporating the CSI feedback process in the medium access control (MAC) layer and the absence of low-overhead but accurate physical-layer models that would allow generation of realistic channel matrices. These challenges currently prevent system-level validation and evaluation of state-of-the-art algorithm designs in IEEE 802.11ax and the upcoming IEEE 802.11be technology.

In this paper, we introduce the implementation of MAC-layer CSI feedback process in ns-3. The code is implemented based on ns-3.37[1]. To the best of the authors' knowledge, this is the first work targeted at integrating the IEEE 802.11ax channel sounding protocol in ns-3. The contributions include:

(1) functionality to generate new frames in ns-3 that are required for channel sounding,
(2) frame exchange logic for channel sounding for both single-user (SU) and multi-user (MU) cases,
(3) functionality to generate well-structured beamforming reports with various choices of CSI resolutions and quantity according to IEEE 802.11ax,[2] and
(4) a simple multi-user scheduler for MU-MIMO, which selects users for channel sounding and MU-MIMO data transmission.

The paper is structured as follows. Section 2 presents preliminaries related to the channel sounding implementation, including introduction of the channel sounding procedure described in the IEEE 802.11ax standard and the high-level code structure of the Wi-Fi module in ns-3. Section 3 describes the code structure and implementation details of the channel sounding protocol. In Section 4, simulation results are demonstrated to validate the implementation and show impact of channel sounding on network throughput and overhead. Finally, Section 5 describes future work and concludes the paper.

[1]The code is available at: https://gitlab.com/jingyuan943/ns-3-dev/-/tree/Wifi-ChannelSounding
[2]Currently, random channel information is used to generate beamforming reports in our implementation. While generation of real channel information is beyond the scope of this paper due to the absence of accurate physical layer models in ns-3, the code is structured so that realistic channel information can be easily turned into a beamforming report if accurate channel modeling is implemented in the future.

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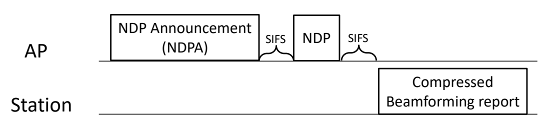
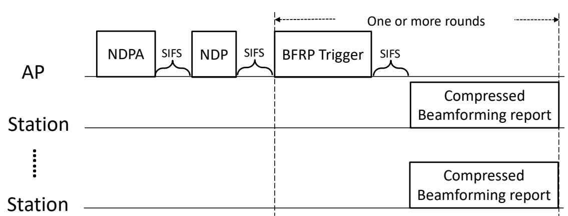
2 PRELIMINARIES

2.1 Channel Sounding in IEEE 802.11ax

In this section, the procedure of channel sounding according to IEEE 802.11ax is introduced [2]. The explicit channel sounding process is shown in Figure 1. The AP first sends a null data packet announcement (NDPA) frame containing information of the stations from which the AP needs to collect CSI. The NDPA frame also specifies the subcarrier grouping, the resolution for CSI quantization, and the frequency range for which the AP requests CSI feedback (both full-bandwidth feedback and partial-bandwidth feedback are allowed). Next, a null data packet (NDP) frame used by stations to measure the channel is transmitted. If this is a channel sounding process in SU case, the station informed by the NDPA frame sends back a beamforming report frame. Otherwise, it is a channel sounding process in MU case and the AP sends a beamforming report poll (BFRP) trigger frame after the NDP frame to solicit the feedback. After the BFRP trigger frame, stations send beamforming report frames using uplink multi-user techniques specified by the trigger frame. Note that several rounds of BFRP trigger frames and beamforming reports are allowed if there are more stations than the maximum number of stations that can be supported by uplink multi-user transmission.



(a) Channel sounding in single-user case



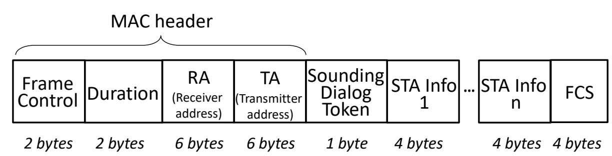
(b) Channel sounding in multi-user case

Figure 1: Illustration of Channel Sounding Process

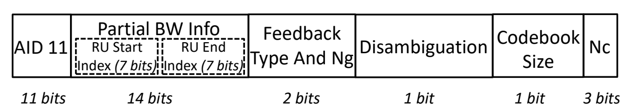
2.2 Frame Formats

This section introduces the formats of two frames implemented in our work: the HE NDPA frame and the HE Compressed Beamforming/CQI frame.

2.2.1 HE NDPA Frame. The format of the High Efficiency (HE) NDPA frame is shown in Figure 2(a). Each NDPA frame contains a list of STA Info subfields, the format of which is shown in Figure 2(b). These subfields specify the parameters that each station will use for CSI feedback. Specifically, the RU Start Index subfield and RU End Index subfield in Partial BW Info indicates the first and the last 26-tone resource unit (RU) for which the beamformer is requiring CSI feedback. The channel sounding type, which can be selected from SU, MU, and channel quality indicator (CQI), as well as the subcarrier grouping parameter N_g and quantization resolution for channel information quantization, are determined by the combined values of the Feedback Type and Ng subfield, along with the Codebook Size subfield. The value for N_g can be chosen as 4 or 16 for SU and MU cases. On each subcarrier, the compressed beamforming matrix is decomposed into two types of angles, represented by Φ and Ψ angles. The number of Φ and Ψ angles on each subcarrier is $N_a/2$, which depends on the number of columns and rows of the compressed beamforming feedback matrix. For SU channel sounding, the number of bits to quantize Φ and Ψ, denoted by (b_Φ, b_Ψ), can be chosen from $(6, 4)$ and $(4, 2)$. For MU channel sounding, the quantization resolution (b_Φ, b_Ψ) can be chosen from $(9, 7)$ and $(7, 5)$. Finally, the Nc subfield determines the number of columns in the compressed beamforming feedback matrix.



(a) HE NDPA frame format



(b) STA Info field format in an HE NDPA frame if the AID11 subfield is not 2047

Figure 2: Illustration of HE NDPA Frame Format

2.2.2 HE Compressed Beamforming/CQI Frame Format. The HE Compressed Beamforming/CQI frame is an Action No Ack frame, the format of which is shown in Figure 3. The Category field determines whether the frame is an HE frame, and the HE Action field is used to detemine whether the frame is a compressed beamforming report frame. The HE MIMO Control field contains information that helps the beamformer to interpret channel information in this frame. The HE Compressed Beamforming Report field and the HE MU Exclusive Beamforming Report field contain all the essential compressed channel information. It is worth noting that the latter only exists in the context of MU channel sounding.

2.3 Wi-Fi MAC-Layer Module in ns-3

In the current ns-3 framework, the Wi-Fi MAC-layer module consists of MAC high models and MAC low layer. MAC high models handles functionality including association, probing, and beaconing, etc. There are three main classes in MAC low layer, which are *FrameExchangeManager*, *Txop*, and *ChannelAccessManager*. The transmission opportunity (TXOP) is an interval of a specified duration during which the station can transmit frames, and the class of *Txop* handles packet fragmentation and retransmission. The class of *ChannelAccessManager* implements distributed coordination function (DCF) and enhanced distributed channel access (EDCA). Frame transmission and reception is handled by *FrameExchangeManager*. Therefore, modification in MAC low layer will be the focus of implementation of channel sounding process.

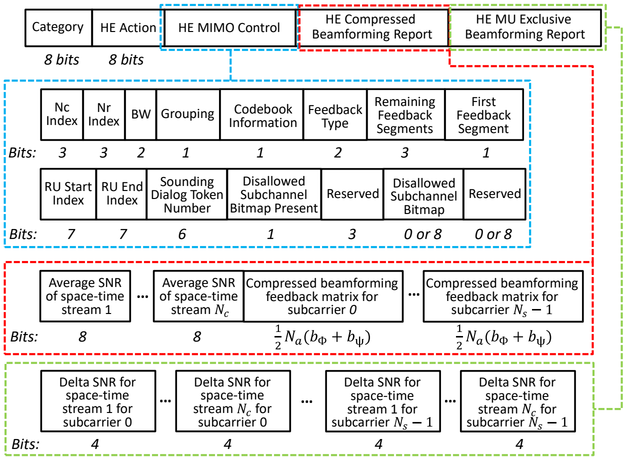


Figure 3: Illustration of HE Compressed Beamforming/CQI Frame Format

3 IMPLEMENTATION OF CHANNEL SOUNDING PROTOCOL

In this section, the details of our MAC-layer channel sounding implementation are introduced. A general description of the code modifications done to implement channel sounding is first presented. Then, the detailed implementation is described in five parts: HE capability configuration, new frames related to channel sounding, management of channel information and channel sounding frames, multi-user scheduling, and frame exchange process.

3.1 Code Structure

A general description of code structure is discussed in this section. All the modified and added classes are as follows.

- Configuration of HE Capability elements related to channel sounding (e.g. subcarrier grouping, codebook resolution for beamforming report, maximum number of columns for compressed beamforming feedback matrix): *HeConfiguration*, *HeCapabilities*, and *WifiMac*.
- Management of channel sounding frame exchange and user scheduling: *HeFrameExchangeManager*, *RrMultiUserScheduler*, *MultiUserScheduler*, *HeRu*, and *WifiTxTimer*.
- New frames related to channel sounding: *WifiMacHeader*, *CtrlTriggerUserInfoField*, *CtrlNdpaHeader* (new class), *WifiActionHeader*, *HeMimoControlHeader* (new class), *HeCompressedBfReport* (new class), and *HeMuExclusiveBfReport* (new class).
- Channel information generation and storage, and channel sounding frame management: *ChannelSounding* (new class), *CsBeamformer* (new class), and *CsBeamformee* (new class).

3.2 HE Capability Configuration

In HE PHY Capabilities Information field, there are multiple elements used to determine CSI resolution, including subcarrier grouping parameter N_g and codebook size which specifies the quantization resolution for Φ and Ψ angles. There are four single-bit fields in HE PHY Capabilities to configure N_g and codebook size in SU and MU cases, respectively. Moreover, there is a three-bit field in HE PHY Capabilities to configure the maximum number of columns of compressed beamforming feedback matrix. Therefore, five attributes are added in the class of *HeConfiguration* as shown in Table 1, and corresponding methods to configure these attributes are added. ns-3 users are allowed to configure these parameters by calling *SetAttribute()*. These attributes are serialized into *HeCapabilities* by adding configuration code in the *WifiMac::GetHeCapabilities* method.

3.3 New Frames

Major changes to existing classes and new added classes necessary to create the frames used in the channel sounding process are introduced in this section.

- NDPA frame
  A new class called *CtrlNdpaHeader* is addded in *ctrl-header.h* and *ctrl-header.cc* to build NDPA control header. The class of *CtrlNdpaHeader* has a member variable named *m_dialogToken* to represent the field of Sounding Dialog Token, along with another member variable named *m_staInfoFields* which contains a list of structs named *StaInfo* storing information in STA Info fields. There are two main methods in the class of *CtrlNdpaHeader*. The first is *AddStaInfoField* which is used to append a given STA Info field to NDPA header. The second is *FindStaInfoWithAid* which is used to get an iterator pointing to the first STA Info field with given AID11.
- BFRP trigger frame
  A new member variable named *m_bfrpTriggerDependentUserInfo* and corresponding methods *SetBfrpTriggerDepUserInfo* and *GetBfrpTriggerDepUserInfo* to set and acquire this variable are added in the class of *CtrlTriggerUserInfoField*.
- Beamforming report frame
  Since the beamforming report frame is a management action frame, a new category value and HE action value to build the management header for this frame are added in the class of *WifiActionHeader*. Moreover, three new classes are added to build the beamforming report frame: *HeMimoControlHeader*, *HeCompressedBfReport*, and *HeMuExclusiveBfReport*. The class of *HeMimoControlHeader* contains all necessary information in the HE MIMO Control field as shown in Figure 3. The classes of *HeCompressedBfReport* and *HeMuExclusiveBfReport* are used to build the HE Compressed Beamforming Report field and the HE MU Exclusive Beamforming Report field, respectively, based on channel information and quantization information provided by *HeMimoControlHeader*.

3.4 Management of Channel Information and Channel Sounding Frames

A base class of *ChannelSounding* and two derived classes called *CsBeamformer* and *CsBeamformee* are created to handle generation of channel information and channel sounding frames.

In the base class of *ChannelSounding*, a struct named *ChannelInfo* with four members is defined to store channel information including: member *m_stStreamSnr* to store average signal-to-noise ratio

Table 1: List of Added Attributes in *HeConfiguration*

Attribute	Definition
NgSu	Subcarrier grouping parameter Ng used in SU channel sounding
NgMu	Subcarrier grouping parameter Ng used in MU channel sounding
CodebookSizeSu	Codebook size of beamforming report for SU channel sounding feedback which can be chosen as $(4, 2)$ or $(6, 4)$
CodebookSizeMu	Codebook size of beamforming report for MU channel sounding feedback which can be chosen as $(7, 5)$ or $(9, 7)$
MaxNc	Maximum number of columns for compressed beamforming feedback matrix

(SNR) for each space-time stream, *m_phi* and *m_psi* to store Φ and Ψ angles, respectively, and *m_deltaSnr* to store the deviation of the SNR in each subcarrier from the average SNR of the corresponding space-time stream, which is used by HE MU Exclusive Beamforming Report field.

The *CsBeamformer* class is a derived class from *ChannelSounding* that is used by the AP to manage channel sounding frames and store channel information acquired from stations. Its main methods and member variables are as follows:

- *GenerateNdpaFrame*: generate NDPA frame given channel sounding information scheduled by the multi-user scheduler.
- *GetBfReportInfo*: read channel information from the beamforming report frame received from stations.
- *CheckAllChannelInfoReceived*: check whether channel information of all the necessary stations is received.
- *CheckChannelSounding*: check whether channel sounding is needed in current TXOP.
- *m_beamformerFrameInfo*: a struct storing NDPA frame, NDP frame and BFRP trigger frame (if it is an MU case) and transmission parameters for these frames.
- *m_channelInfoList*: a list of struct *ChannelInfo* storing channel information acquired from different stations.

The *CsBeamformee* class is a derived class from *ChannelSounding* that is used by the station to manage channel sounding frames and generate channel information. Its main methods and member variables are:

- *CalculateChannelInfo*: generate random information for the compressed beamforming feedback matrix[3].
- *GetNdpaInfo* and *GetNdpInfo*: get necessary information in NDPA and NDA frames sent from the AP.
- *GenerateBfReport*: generate beamforming report frame given channel information.
- *m_channelInfo*: a struct of *ChannelInfo* storing generated channel information.
- *m_heMimoControlHeader*: a member variable with type *HeMimoControlHeader* containing all the necessary information to acquire and quantize channel information.

3.5 Multi-User Scheduling

In our implementation, a simple round robin multi-user scheduler is added to select users for channel sounding. The goal of the simple scheduler is to select as many users as possible while ensuring that channel sounding can be finished within given time.

[3]Random channel information is currently used due to the current lack of a detailed and efficiently computable channel model in ns-3.

In our implementation, channel sounding is triggered periodically with a tunable interval, and the impact of various interval values on network performance is studied in Section 4.2. The scheduler calls the method *CsBeamformer::CheckChannelSounding* to determine if channel sounding is required in the current TXOP. If channel sounding is required, *RrMultiUserScheduler::TryChannelSounding* is called to schedule users for CSI feedback. Since the goal is to collect CSI to support the following downlink data transmission, users for channel sounding are selected from a list of candidate stations with downlink packets waiting to be transmitted. Users are added one by one and then the duration of the channel sounding process is estimated to check whether it is within the current TXOP. The process ends when the channel sounding duration exceeds the TXOP limit or the maximum number of supported users is reached.

The generation of the NDPA frame, NDP frame and BFRP trigger frame (if it is an MU case), along with necessary transmission parameters, is done by the scheduler during the user scheduling process. This information is stored in a member variable called *m_beamformerFrameInfo* in the *CsBeamformer* class, thereby allowing *HeFrameExchangeManager::StartFrameExchange* to transmit these frames from the AP later on.

For the MU case, orthogonal frequency-division multiple access (OFDMA) is used for simultaneous CSI feedback from multiple stations. Specifically, the allocation of equal-sized RUs to various stations is implemented, and the use of central 26-tones RUs can also be enabled. The method of *HeRu::GetEqualSized-RusForStations* is modified to allowed equal-sized RU allocation given the number of stations. Available RUs, excluding the central 26-tones RUs, will be allocated first. However, if the number of stations surpasses the number of available RUs and central 26-tones RUs are enabled, central 26-tones RUs are allocated to accommodate as many extra stations as possible. Any station that cannot be allocated an RU is excluded from the current round of channel sounding.

If there is remaining time in the current TXOP after channel sounding is completed, the scheduler will schedule as many users as possible for data transmission in the same TXOP. Otherwise, data transmission will be scheduled in a new TXOP. Only users with successful CSI feedback are considered for data transmission.

3.6 Frame Exchange Process

In this section, the frame exchange process for channel sounding is described, first from the AP perspective and then on the station side.

- Frame transmission at AP
  To start channel sounding process and begin transmission of control frames at AP, modifications have been made in the

functions *RrMultiUserScheduler::SelectTxFormat*, *HeFrameExchangeManager::StartFrameExchange*, and *HeFrameExchangeManager::ReceiveMpdu*. To determine the type of transmission in the current TXOP, the function *RrMultiUserScheduler::SelectTxFormat* is called. This function calls *CsBeamformer::CheckChannelSounding* to determine whether channel sounding is needed in the current TXOP based on the time interval. Once *RrMultiUserScheduler::SelectTxFormat* determines the occurrence of channel sounding, *HeFrameExchangeManager::StartFrameExchange* schedules the transmission of NDPA frame, NDP frame, and BFRP trigger frame if this is an MU case.

Once the NDP frame is sent out for an SU case or the BFRP trigger frame is sent out for an MU case, a timer is set to wait for beamforming reports from stations. Modifications were made in *HeFrameExchangeManager::SendPsduMapWithProtection* to enable the timer and a new timer type corresponding to channel sounding process is added in the class of *WifiTxTimer*.

Modifications in *HeFrameExchangeManager::ReceiveMpdu* have been made to handle reception of beamforming report feedback at AP. The recognition of a beamforming report frame depends on operation of the timer and the type of packet received. Specifically, if a packet received while the timer is running is an Action No Ack frame, it will be identified as a beamforming report frame. Conversely, if an Action No Ack frame is not received while the timer is running, or a packet received while the timer is running is not an Action No Ack frame, the packet will be discarded. Then *CsBeamformer::CheckAllChannelInfoReceived* is called to check whether beamforming reports from all stations specified in the NDPA frame were collected. If beamforming reports from all the necessary stations were received, the timer is terminated at once. Otherwise, the timer keeps running.

Channel sounding is reported as successful if at least one beamforming report is received within the time-out duration. After this, *HeFrameExchangeManager::StartFrameExchange* is called again to schedule data transmission among stations from which CSI was received. However, if the AP does not receive any beamforming reports within the time-out duration, the current transmission is reported as failed and the current TXOP is given up.

- Frame transmission at station
To enable frame transmission of channel sounding at stations, modification is made in *HeFrameExchangeManager::ReceiveMpdu*. Once a station receives an NDPA frame, it checks whether it will be involved in channel sounding process by matching its station ID with STA Info field in the NDPA frame.

If the station is involved in the channel sounding process, it waits for the NDP frame, and the BFRP trigger frame if it is an MU case (A station identifies the channel sounding process as an MU case if there are multiple STA Info fields in NDPA). If NDP frame is received, the station calls *CsBeamformee::CalculateChannelInfo* to calculate channel information (Note that only random channel information is generated in this function currently). After calculating channel information, the station calls *CsBeamformee::GenerateBfReport* to generate its beamforming report packet. However, if the NDP frame or the BFRP trigger frame (if it is an MU case) is not received by a station, the station will not participate in the channel sounding process.

If the NDPA frame indicates SU channel sounding, the station schedules transmission of its beamforming report after reception of the NDP frame. If NDPA indicates MU channel sounding, the station schedules transmission of its beamforming report after reception of BFRP trigger frame and uses uplink MU transmission techniques and parameters specified in the trigger frame.

4 SIMULATION

In this section, simulation results are presented to validate our channel sounding implementation and evaluate channel sounding overhead as a function of several important parameters. Let N_r and N_c be the number of rows and columns in a compressed beamforming report matrix, and N_g denote the subcarrier grouping parameter that is either 4 or 16. The codebook size, (b_Φ, b_Ψ), is defined as the number of bits to quantize Φ and Ψ angles in the compressed beamforming report matrix. Possible values for (b_Φ, b_Ψ) are $(4, 2)$ and $(6, 4)$ for the SU case, and $(7, 5)$ and $(9, 7)$ for the MU case.

The following parameters are used for all results in this section. The operation frequency is set to 5 GHz. Since the current implementation supports up to 4 antennas per device, we fix the number of antennas on the AP to 4 and assume that each station has at most 4 antennas. Thus, $1 \leq N_c \leq N_r \leq 4$. In all the reported simulations, the AP requests channel information for the entire band and the central 26-tones RUs are disabled for both CSI feedback and data transmission. It is also assumed that only one stream is supported from each station to the AP for beamforming report transmission.

4.1 Impact of Channel Sounding on Latency

Although MU-MIMO has the potential to increase aggregate rate in a data transmission slot, the channel sounding process requires a non-negligible amount of time. In this section, we use our implementation of the MAC-layer channel sounding process to evaluate this overhead and investigate the impact of various channel sounding parameters on it. In Section 4.1.1 and Section 4.1.2, the worst case of modulation coding scheme (MCS) (HE MCS0), the smallest sub-carrier grouping (4), and the largest codebook sizes ((6, 4) for SU and (9, 7) for MU) are considered when investigating the impact of other channel sounding parameters. Those results, therefore, represent the worst case channel sounding duration for the different parameter choices.[4] The impact of larger sub-carrier

[4]The channel sounding duration is the time required for the *entire* channel sounding process, i.e. the time from when the sending of the NDPA frame begins until the last bit of the beamforming report frames is received. The channel sounding duration is measured in the context of no channel sounding packet loss. Therefore, the duration is strictly determined by bandwidth, subcarrier grouping and quantization resolution. Thus, each data point in the figures in this section represents the duration of a single channel sounding frame exchange with a given choice of parameters.

grouping, smaller codebook sizes, and higher data rates on reducing the sounding duration is then discussed in Section 4.1.3 and Section 4.1.4.

4.1.1 Worst-Case Channel Sounding Duration vs. Number of Stations. Figure 4 shows the duration of channel sounding vs. the number of stations. The SU channel sounding scheme, as shown in Figure 1(a), is implemented when there is only one station, whereas the MU scheme illustrated in Figure 1(b) is employed if there is more than one station. In addition to the worst-case values selected for MCS level, sub-carrier grouping, and codebook size as stated earlier, the maximum dimensions of the channel matrix were selected, i.e. $(N_r, N_c) = (4, 4)$. The first thing to notice is that, even with parameter choices designed to maximize CSI overhead, the duration of CSI exchange is short for the single-user case. The duration increases with the number of stations and is clearly non-negligible with 3 and 4 stations for these worst-case parameter values. Later sections will show how much the overhead is reduced for other values of sub-carrier grouping, codebook size, and MCS level.

The results also show that the sounding duration generally decreases as the channel bandwidth increases. Although the amount of CSI increases with the channel bandwidth, the capacity of the channel to transmit the beamforming reports also increases, which shortens the time required to transmit beamforming report packets.

Finally, there is a seeming anomaly in that the overhead with 3 stations is nearly the same as with 4 stations. This is due to a limitation in how resource units are currently assigned in ns-3, which only allows the band to be fully covered with equal-sized resource units if there is an even number of stations. If more flexible resource allocation is supported in ns-3 in the future, then the overhead of 3-station channel sounding can be reduced.

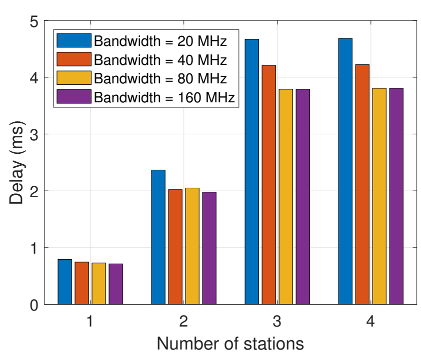


Figure 4: Sounding Duration vs. Number of Stations (Nr = 4, Nc = 4, Ng = 4, Codebook Size = (6,4) and (9,7), HE MCS0)

4.1.2 Worst-Case Channel Sounding Duration vs. Size of Compressed Beamforming Report. In this section, the impact of the size of the compressed beamforming report matrix on channel sounding overhead is investigated. Figure 5 shows the results given that $N_g = 4$, (b_1, b_2) is $(6, 4)$ for SU and $(9, 7)$ for MU and the channel bandwidth is 160 MHz. Moreover, HE MCS0 is used to transmit the beamforming report frame and there are 4 stations involved in channel sounding for the MU case. According to Figure 5, the channel sounding duration in the SU case has a 140% increase when the matrix size increases from $(2, 1)$ to $(4, 4)$, while the increase is nearly 300% in the MU case. The results indicate that the overhead in the SU case is less sensitive to the size of the compressed beamforming feedback matrix than in the MU case. Apart from the impact of resource allocation, another reason is that there is an extra field called the HE MU Exclusive Beamforming Report field in the MU format of the beamforming report frame.

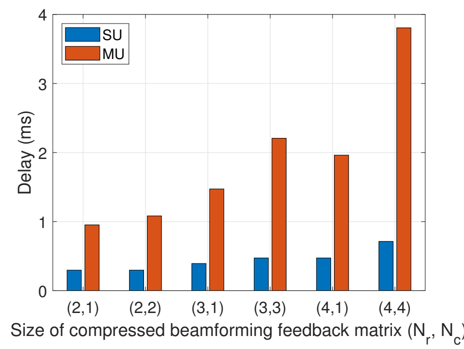


Figure 5: Sounding Duration vs. Size of Beamforming Feedback Matrix (N_r, N_c) (Bandwidth = 160MHz, Ng = 4, Codebook Size = (6,4) and (9,7), HE MCS0, 4 Stations for MU Case)

4.1.3 Overhead Reduction by Adjustment of Subcarrier Grouping and Codebook Size. Based on the results in Section 4.1.1 and Section 4.1.2, the channel sounding duration can be 4–5 ms at the lowest MCS level if the number of stations and the size of compressed beamforming feedback matrix are at the higher end of their ranges. One way to reduce the overhead from this rather large value is to adjust the codebook size and subcarrier grouping. Herein, both the smallest and largest sizes of beamforming report frames are considered, corresponding to the SU case with beamforming matrix size $(N_r, N_c) = (2, 1)$ and the MU case with 4 stations and beamforming matrix size $(N_r, N_c) = (4, 4)$, respectively.

The impact of subcarrier grouping on channel sounding duration is shown in Figure 6. Herein, the channel bandwidth is 160 MHz and the codebook sizes are (6,4) for the SU case and (9,7) for the MU case. As the subcarrier grouping parameter, N_g, increases from 4 to 16, the overhead reduction for the four cases, which are SU with $(N_r, N_c) = (2, 1)$, SU with $(N_r, N_c) = (4, 4)$, MU with $(N_r, N_c) = (2, 1)$, MU with $(N_r, N_c) = (4, 4)$ are 21%, 49%, 47% and 67%, respectively. Sounding durations for all four cases are reduced below 1.5 ms.

The impact of codebook size on channel sounding duration is shown in Figure 7. The subcarrier grouping parameter is set as 4. As codebook size is reduced from (6,4) to (4,2) for SU case and reduced from (9,7) to (7,5) for MU case, the overhead reduction for the four cases are 11%, 27%, 12% and 19%, respectively. The sounding duration for the case with the largest beamforming report size, which is the MU case with $(N_r, N_c) = (4, 4)$, is still more than 3 ms. Moreover, the percentages of overhead reduction for all four cases are lower with codebook size adjustment compared with subcarrier grouping adjustment.

In conclusion, it is more effective to reduce channel sounding duration by tuning the subcarrier grouping than the codebook size.

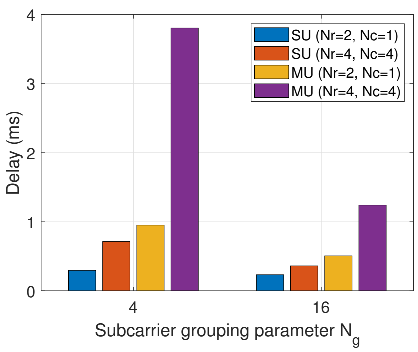


Figure 6: Sounding Duration vs. Subcarrier Grouping (Bandwidth = 160MHz, Codebook Size = (6,4) and (9,7), HE MCS0, 4 Stations for MU Case)

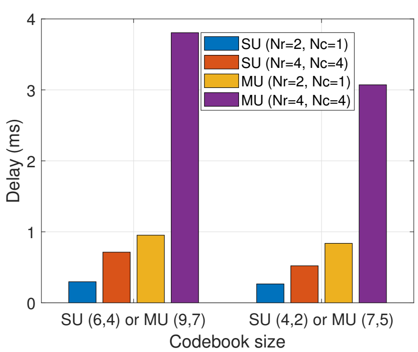


Figure 7: Sounding Duration vs. Codebook Size (Bandwidth = 160MHz, Ng = 4, HE MCS0, 4 Stations for MU Case)

4.1.4 Overhead Reduction with Higher MCS Levels. In previous sections, channel information is sent back to AP with HE MCS0, corresponding to the lowest data rate. In this section, the influence of the MCS level on channel sounding duration is investigated. Herein, the channel bandwidth is set as 160 MHz and the largest size of the compressed beamforming feedback matrix is considered such that $(N_r, N_c) = (4, 4)$. According to Figure 8, as MCS for higher data rates is used, the sounding durations for both SU and MU reduce significantly. The duration for the SU case reduces from 0.71 ms to 0.25 ms as the MCS varies from HE MCS0 to HE MCS11, demonstrating a 65% reduction. In the MU case, the duration reduction is more significant, decreasing from 3.81 ms to 0.57 ms, which is a 85% reduction. The results indicate that the MU channel sounding overhead is not too substantial when channel conditions permit an MCS level of 4 or higher but that the overhead can be much higher when channel conditions force the lowest MCS levels to be used or those levels are chosen for other reasons, e.g. reliability or power savings.

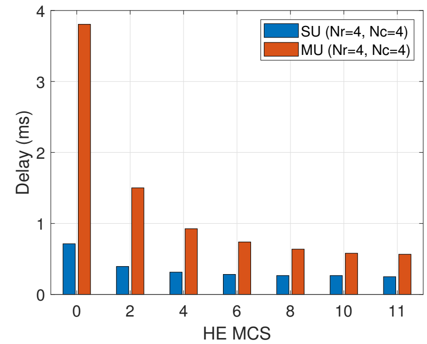


Figure 8: Sounding Duration vs. MCS (Bandwidth = 160MHz, Ng = 4, Codebook Size = (6,4) and (9,7), 4 Stations for MU Case)

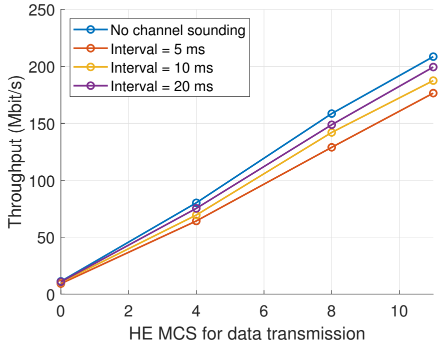
4.1.5 Range of Channel Sounding Duration. To provide bounds on channel sounding overhead, the range for the sounding duration is given in this section. Based on the results in Section 4.1.1, the worst case is the MU case in a 20 MHz channel with the maximum number of stations, lowest data rate, and largest size of beamforming report frame. Therefore, channel sounding parameters should be selected as $N_g = 4$, $(N_r, N_c) = (4, 4)$ and codebook size $(b_\Phi, b_\Psi) = (9, 7)$. Considering the maximum number of stations in our simulation is four and the lowest MCS is HE MCS0, the maximum channel sounding duration is 4.68 ms, which is non-negligible compared with data packet transmission time.

Conversely, the best case is the SU case in a 160 MHz channel with highest data rate and smallest size of beamforming report frame. Therefore, the channel sounding parameters should be $N_g = 16$, $(N_r, N_c) = (2, 1)$ and codebook size $(b_\Phi, b_\Psi) = (4, 2)$. Moreover, MCS should be selected as HE MCS11. With these parameters, the minimum channel sounding duration is 0.23 ms.

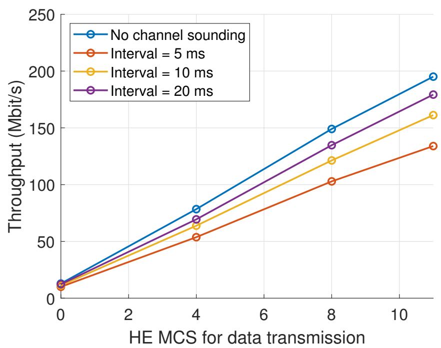
4.2 Impact of Channel Sounding on Throughput

In this section, the impact of periodic channel sounding on throughput is investigated. The traffic is generated by the User Datagram Protocol (UDP) with a packet size of 700 bytes. Moreover, constant transmission rate is used for every data packet. Throughput reported in all figures in this section represent the aggregated throughput over all stations. It should be emphasized that, since there is currently no PHY layer model in ns-3 for MU-MIMO, the results in this section do not take into account the impacts of MIMO beamforming, inter-stream interference cancellation, and channel aging. The results simply aim to show, under an idealized throughput model ignoring the above effects, how much impact the channel sounding overhead has on throughput and how that varies with the channel sounding interval and several other parameters.

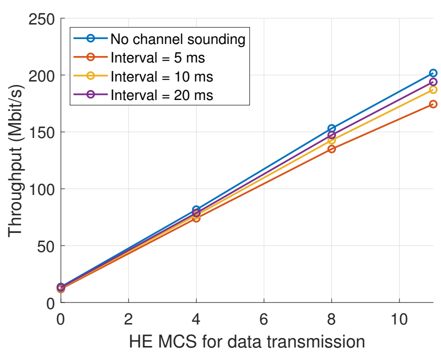
The channel sounding interval plays an important role in throughput performance. A shorter interval brings heavier channel sounding overhead but can mitigate throughput reduction caused by channel aging. Therefore, the tradeoff between the channel sounding interval and channel aging is one of the critical problems to improve network throughput. Herein, how the interval influences



(a) Scenario 1: 2 stations with 1 stream per station, $(N_r, N_c) = (4, 1)$



(b) Scenario 2: 2 stations with 2 streams per station (only 1 station is selected for downlink data transmission), $(N_r, N_c) = (4, 2)$



(c) Scenario 3: 1 station with 2 streams, $(N_r, N_c) = (4, 2)$

Figure 9: Throughput for Different Channel Sounding Intervals (Bandwidth = 20 MHz, HE MCS0 for Beamforming Report Feedback)

throughput is investigated without considering channel aging due to the lack of an accurate time-varying channel model in ns-3.

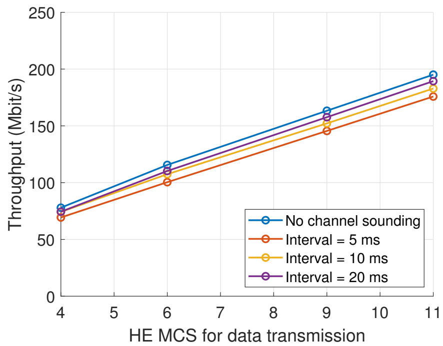
In the results reported in this section, the subcarrier grouping parameter $N_g = 4$, and the codebook size is $(6, 4)$ for SU-MIMO and $(9, 7)$ for MU-MIMO. We set the number of antennas on the AP to four and transmit two streams in total. This allows us to simulate and compare three different scenarios, which are described below. For these three scenarios, HE MCS0 is used for all beamforming report feedback while the MCS level for data transmission can vary.

Scenario 1: There are two stations, each with a single antenna. The AP collects CSI from both stations and then transmits one stream to each station by using downlink MU-MIMO. The size of compressed beamforming feedback matrix is $(N_r, N_c) = (4, 1)$. This case represents a null steering scenario where the AP uses two degrees of freedom to transmit data streams and uses another two degrees of freedom to cancel inter-user interference. Results for Scenario 1 are shown in Figure 9(a).

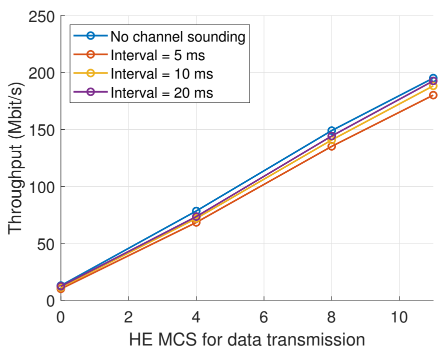
Scenario 2: There are two stations, each with two antennas. The AP collects CSI from both stations and then transmits two streams to only one selected user. The size of compressed beamforming feedback matrix is $(N_r, N_c) = (4, 2)$. This case represents a scenario where the AP tries to maximize throughput by selecting the user with the best channel condition. Since there is currently no explicit channel model in ns-3, a random station is selected by the AP. Results for Scenario 2 are shown in Figure 9(b). Any packets generated for the station not chosen will be disregarded.

Scenario 3: There is one station with two antennas. The AP collects CSI from this station and then transmits two streams to it. The size of compressed beamforming feedback matrix is $(N_r, N_c) = (4, 2)$. Results for Scenario 3 are shown in Figure 9(c).

Note that the "no channel sounding" curve in each of the plots is an upper bound on throughput under the idealized conditions simulated herein, because there is zero overhead for channel sounding in that scenario. Also, as the channel sounding interval becomes shorter (sounding frequency increases), the throughput drops monotonically in each scenario, as is expected. The greatest impact on throughput occurs for Scenario 2. This is because, along with Scenario 3, it has the largest channel matrix feedback $(4, 2)$ but each station is only allocated half the channel bandwidth for its beamforming report, whereas in Scenario 3, the single user can use the entire channel for its CSI feedback. The largest throughput reduction overall is 31% and occurs in Scenario 2 with a channel sounding interval of 5 ms (orange curve in Figure 9(b)) and an MCS of 11 for data transmission. When the channel sounding interval is increased to 20 ms, this same case experiences a performance decrease of less than 11%, indicating that lowering the frequency of channel sounding could potentially increase performance. This must, of course, be understood to be in the context of no loss of CSI quality over the channel sounding interval. If the channel coherence time is less than the sounding interval, CSI quality will be degraded, which could easily outweigh any gains due to reduction in the overhead of CSI collection. If the channel dynamics are well understood for a given environment of interest and can be incorporated into the simulator, a meaningful study of the impact of CSI collection frequency on performance could be carried out with our code. Next, the impact of the MCS level used for beamforming report frames is investigated. This evaluation focuses on Scenario 2, which incurs the highest channel sounding overhead among these considered scenarios. Rather than fix the MCS for beamforming feedback report as HE MCS0, HE MCS4 is used for feedback in Figure 10(a) while MCSs for beamforming feedback report and data transmission are assumed to be the same in Figure 10(b). Considering practical power limitation at users, it can be assumed that uplink MCS cannot exceed downlink MCS. Therefore, only results of data transmission with MCS higher than or equal to HE MCS4



(a) HE MCS 4 is used for beamforming report feedback



(b) Same HE MCS is used for beamforming report feedback and MU-MIMO data transmission

Figure 10: Throughput for Different Channel Sounding Intervals (Bandwidth = 20 MHz, Scenario 2)

are shown in Figure 10(a). Compared with Figure 9(b), where HE MCS0 is used for beamforming reports, throughput improvement can be observed in Figure 10(a) when the MCS for beamforming report frames is increased to HE MCS4. In Figure 9(b), throughput reduction is in the range of 30–32% with HE MCS0 for CSI feedback, HE MCS4 to HE MCS11 for data transmission and channel sounding interval of 5 ms, while the reduction decreases to the range of 10–13% in Figure 10(a) with the same interval but HE MCS4 for CSI feedback. Interestingly, if the power constraint at users is not considered and a higher MCS level is used for both uplink CSI feedback and downlink data transmission, as shown toward the right side of Figure 10(b), there is very little additional benefit, as compared to using HE MCS4 for beamforming report frames, as was done in Figure 10(a). This aligns with the results in Figure 8, which showed that the duration of channel sounding is reduced significantly when the MCS of beamforming report feedback increases from HE MCS0 to HE MCS4, while the reduction diminishes as the MCS increases beyond HE MCS4. The reason for this is that the MCS used for control frame transmission is usually low and increasing MCS for beamforming report frame beyond a certain amount will not have a substantial impact on the overall duration. These results indicate that, under high SNR conditions, choosing a moderate MCS level for beamforming report frames, e.g. HE MCS4, can both decrease channel sounding overhead significantly and achieve good reliability for beamforming report frame transmission.

5 CONCLUSION AND FUTURE WORK

In this paper, a channel sounding frame exchange implementation in ns-3 was introduced. The implementation provides the functionalities of channel sounding frame generation and support of frame exchange logic and multi-user scheduling for channel sounding and MU-MIMO data transmission. The channel sounding functionality was validated by simulation results that also provide a preliminary analysis of its impact on latency and throughput.

In future work, the implementation will be refined as follows:

(1) add support for compressed beamforming feedback matrix with number of rows or columns up to 8 (maximum of 4 is supported currently),
(2) add a retransmission scheme when one or more beamforming reports are not correctly received at the AP, and
(3) address the issue of a possible change in available bandwidth when channel sounding and data transmission are scheduled in different TXOPs.

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