An Implementation Proposal for IEEE 802.11ay SU/MU-MIMO Communication in ns-3

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ABSTRACT

Wireless communications in the millimeter-wave band bring unprecedented capabilities to achieve wireline performance in wireless networks and alleviate the congestion problem of current wireless technologies. However, efficient wireless networking in this band is extremely challenging compared to wireless technologies operating in the microwave band. IEEE 802.11ay is the next generation multi-gigabit standard to support wireless networking at 60 GHz. It is envisioned to support extremely high data-rates of up to 300 Gbps, achieved through new complex physical layer techniques including MIMO communication, channel bonding and aggregation, and high order-modulation schemes. Simulating the IEEE 802.11ay standard in a network-level simulator requires accurate abstraction models to incorporate the effects of those techniques. At the time of writing, ns-3, a system-level simulator widely used by the scientific community, still lacks support for MU-MIMO communication. Additionally, it requires generating environment dependent SNR-to-BER look-up tables to accurately simulate SU-MIMO communication. In this paper, we propose a hybrid implementation that includes minimum signal processing blocks to accurately simulate IEEE 802.11ay SU/MU-MIMO communication in ns-3 with high accuracy and reduced computational complexity.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Wireless local area networks**;

KEYWORDS

Millimeter Wave, IEEE 802.11ad, IEEE 802.11ay, 60 GHz, WiGig, MIMO, ns-3, Simulations

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1 INTRODUCTION

The main goals of the next generation wireless and mobile networks are ubiquitous connectivity, a high number of connected devices, ultra high-speed links, and extremely low latency. Communication in the millimeter-wave (mmWave) band fulfills all the aforementioned requirements and paves the way for a new set of applications that are not possible with the existing wireless technologies such as 4G/LTE and 802.11n/ac standards. The IEEE 802.11ad was the first wireless local area networks (WLAN) standard that utilizes the 60 GHz band and provides multi-gigabit throughput over the air using both Single Carrier (SC) and Orthogonal Frequency Division Multiplexing (OFDM) physical (PHY) technologies. The use cases for IEEE 802.11ad range from ultra high definition video streaming and HDMI cable replacement to fast file synchronization. Despite the very high throughput provided by IEEE 802.11ad, it is still insufficient for some applications such as wireless back-hauling and front-hauling solutions. IEEE 802.11ay is the next generation mmWave standard that employs a variety of techniques to dramatically increase PHY capacity and throughput from 7 Gbps to up to 300 Gbps. This is mainly achieved by introducing complex PHY techniques, including multiple-input and multiple-output (MIMO) communication, channel bonding and aggregation [7].

At the time of writing, the ns-3 WiFi module does not provide sufficient support for MIMO communication. The only support of MIMO in ns-3 is a basic optimistic implementation of a single user (SU)-MIMO, where the throughput is increased by a fixed ratio depending on the SU-MIMO configuration. This approach was used for simplicity and scalability but has rather low fidelity. Accurately representing SU/multi-user (MU)-MIMO communication requires intensive signal processing operations first to estimate and extract the coefficients of the wireless channel and then, to perform digital precoding to eliminate or reduce inter-stream interference. Simulating the complete signal processing chain would make network-level simulations last longer and more complex to analyze. For these reasons, network-level simulators rely on PHY layer abstraction techniques, which must be carefully chosen in order to guarantee results close to real-PHY behaviour.

In this paper, we survey different options for implementing SU/MU-MIMO communication for the IEEE 802.11ay standard in ns-3, and we compare their advantages and disadvantages. Finally, we provide a proposal for the design of a system that incorporates minimum signal processing steps to simulate SU/MU-MIMO communication with high fidelity and low computational complexity.

2 MILLIMETER-WAVE MIMO SYSTEMS

Wireless communication in the mmWave band requires the use of steerable Phased Antenna Arrays (PAAs) to generate analog beams and focus the energy towards the intended receiver. Achieving full digital beamforming requires a dedicated Radio Frequency (RF) chain per each antenna element in the PAA. This approach is not practical due to both high cost and high power consumption of the digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) operating for high bandwidth signals. For these reasons, different hybrid beamforming architectures that combine both analog and digital beamforming have been proposed in the literature [1]. In these approaches, a single RF chain is connected to a subset of the antenna elements. Figure 1 illustrates the partially connected beamforming architecture. In this architecture, each RF chain is connected to a single PAA or a sub-array of a larger PAA. Also multiple PAAs can be connected to a single RF chain, but then only one of those PAAs is active at a time. The baseband precoder maps N_{TX} spatial streams to N_{RF} chains. Hybrid approaches are practical, consume less power, and achieve similar performance to fully digital beamforming architectures [10].

However, the joint design of analog and digital beamforming is a rather challenging task. For this reason, mmWave wireless systems tend to perform beamforming training in two-stages. In the first stage, the two communicating devices perform analog beamforming training using coarse analog beams of the PAA. However, these coarse analog beams introduce inter-stream interference among the spatial streams at the receiver. As a result, in the second stage, the two communicating devices perform digital precoding or digital beamforming in which the receiver estimates the equivalent baseband channel and feeds it back to the transmitter. The equivalent baseband channel contains the Channel State Information (CSI) between each pair of transmit and receive PAA. Then, the transmitter builds a spatial mapping matrix Q to eliminate inter-stream interference. The IEEE 802.11ay standard defines a set of procedures to perform beamforming training for both SU-MIMO and MU-MIMO communications. These procedures allow devices to determine the best transmit and receive antenna configuration for simultaneous transmission and receptions of multiple spatial streams. In the following sections, we provide a brief background on SU/MU-MIMO communication in the IEEE 802.11ay standard and how to simulate it in ns-3.

2.1 SU-MIMO Communication

2.1.1 Background. In this communication mode, a single data stream is scrambled, encoded, and then mapped to multiple spatial streams N_{SS}. For each spatial stream, the transmitter can use an independent modulation and coding scheme (MCS). If space-time block coding (STBC) is enabled, then each single spatial stream will be further mapped to two space-time streams. In that case, a transmitted stream over the air does not correspond to a single medium access control (MAC) frame but rather to the symbols of a fraction of that frame. Then, for each spatial stream, we generate an independent preamble and header fields. Finally, the space-time streams N_{STS} are mapped to multiple transmit chains N_{TX} based on a spatial mapping matrix Q.

To simulate SU-MIMO in ns-3, we need to implement the previous signal processing chain at the transmitter and its corresponding part at the receiver, which increases computational complexity and thus simulation runtime. The authors in [8] integrated the OFDM PHY layer of the IEEE 802.11a/p standards in ns-3 and found that simulation runtime increased by a factor of 300 to 14000. The increase depends on many factors including the amount of generated traffic, packet sizes, and the number of simulated stations. We expect this to be even worse when simulating the IEEE 802.11ad/ay PHY layer. Indeed, this standard can generate gigabits of throughput per second which results in tens of thousands of packets per second. On the other hand, simulating the whole signal processing chain improves simulation accuracy.

The current implementation of SU-MIMO for the IEEE 802.11n/ac standards in ns-3 abstracts all the signal processing steps to generate and transmit multiple parallel spatial streams N_{SS}. Specifically, transmitting multiple N_{SS} affects only the number of OFDM symbols in the payload part of the transmitted frame. This approach requires generating an offline lookup table (LUT) for mapping Signal-to-Noise Ratio (SNR) to packet error rate (PER). The SNR in this case is an effective SNR value that incorporates all the spatial streams SNRs. However, this approach requires generating a large set of LUTs based on the number of transmit and receive PAAs, and the type of channel between each pair of transmit and receive antennas. For this reason, such an approach does not scale well for dense scenarios.

The scalability of the LUTs method is even worse when simulating SU-MIMO in the mmWave band. This is because the mmWave channel is very sparse and few multipath components (MPCs) exist between pairs of transmit and receive PAAs. As a result, transmitting multiple spatial streams is not always feasible as it depends on channel diversity to multiplex these spatial streams. Additionally, since PAAs within the same device are located close to each other, analog beamforming is not sufficient to separate the concurrent streams and avoid inter-stream interference at the receiver side. For these reasons, we need to generate an extensive set of LUTs to consider both channel condition for each channel instance and the digital precoding technique utilized to orthogonalize the spatial streams at the receiver.

2.1.2 Implementation Proposal. Figure 2 shows the building blocks for our proposal to simulate SU/MU-MIMO for the IEEE 802.11ay standard in ns-3. We will build our ns-3 IEEE 802.11ay MIMO module on top of our future IEEE 802.11ay implementation, which will reuse the IEEE 802.11ad ns-3 implementation [3–6]. We explain in detail each block:

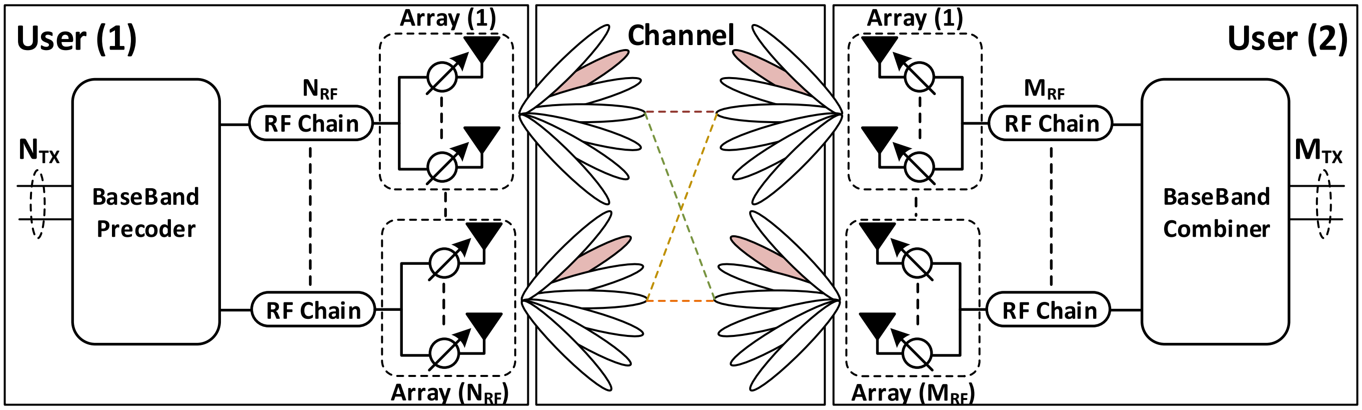

Figure 1: SU-MIMO Partially Connected Beamforming Architecture

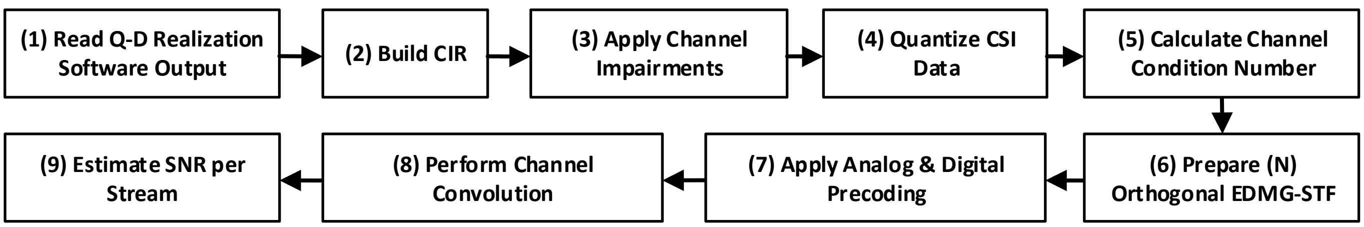

Figure 2: MIMO Simulation Blocks for IEEE 802.11ay in ns-3

(1) We generate Quasi-Deterministic (Q-D) channel traces using our Q-D realization software [2].
(2) The generated trace files include all the MPCs in the simulated environment, allowing to construct the Channel Impulse Response (CIR) between each pair of transmit and receive PAAs. As a result, we get the full channel matrix $H_{BB}(t, \tau)$. This step eliminates the channel estimation on a per-packet basis.
(3) Then, we apply the effects of channel impairments on the CIR to emulate the channel estimation error. These effects include carrier frequency offset (CFO), Phase Noise (PN), non-linearity in the amplifiers, and Symbol timing offset (STO). Executing this step is optional.
(4) Here, we quantize the calculated CSI to emulate quantization errors in real systems where devices use a limited number of bits.
(5) Based on the quantized CSI information, we compute the channel condition number to estimate the number of N orthogonal spatial streams the fading channel can support. The channel condition number depends on the Eigenvalues of the channel matrix and is not impacted by analog and digital precoding.
(6) At this point, we start the data transmission phase by constructing N orthogonal enhanced directional multi gigabit (EDMG)-short training field (STF) fields as defined in the IEEE 802.11ay standard.
(7) We perform both analog and digital precoding to these EDMG-STFs. The analog precoding works as a spatial filter to the CIR whereas the digital precoding reduces inter-stream interference. We perform digital precoding using one of the existing techniques, e.g., zero-forcing (ZF) or minimum-mean-squared-error (MMSE).
(8) Then, we perform channel convolution on the previous EDMG-STF fields.
(9) We estimate the signal-to-interference-plus-noise ratio (SINR) for each stream from the convoluted EDMG-STF fields. The EDMG-STF field contains long repetitions of identical Golay sequences, which allows estimating the noise of the signal. Additionally, the number of transmitted spatial streams is known, and these streams are orthogonal due to the properties of the utilized Golay sequences, and we can thus estimate the power of all the streams at all the PAA. Finally, we map the SINR value for each stream to PER value. If the receiver has multiple PAAs, we map the SINRs values of all its streams to an effective PER value.

While our proposal introduces extra processing overhead and increases simulation runtime, it avoids generating a high number of LUTs to consider all the possible configurations for each simulated scenario. However, it is still necessary to generate a few LUTs that map the SNRs of multiple streams at each receiver to an effective PER value. The heavy computation and processing overhead come from the operations related to constructing the full channel matrix $H_{BB}(t, \tau)$ between all the transmit and receive PAAs. This step has to be executed every time a single channel instance between a single pair of transmit and receive PAAs changes, for example, due to mobility. In summary, our implementation proposal is a compromise between performing symbol-level simulations and completely abstracting PHY layer operation.

2.2 MU-MIMO Communication

In MU-MIMO communication, an access point (AP) transmits multiple spatial streams to different users at the same time. The number of users can be more than the number of transmit chains at the AP. For these reasons, researchers have been proposing different user scheduling algorithms for MU-MIMO systems. These algorithms select which group of users should participate in the current MU-MIMO transmission to increase overall system capacity [9].

At the time of writing, the WiFi module in ns-3 lacks support for MU-MIMO. To simulate IEEE 802.11ay MU-MIMO communication in ns-3, we propose two implementations based on network complexity. In the first implementation, we assume that each user in the network has a single RF chain connected to a single PAA to transmit and receive a spatial stream. In addition, the AP has multiple RF chains, but it transmits a single spatial stream per user. As a result, each spatial stream corresponds to a data packet from the MAC layer for a specific user. Additionally, we consider that analog beamforming can generate orthogonal beams to avoid inter-stream interference at each user and thus we can omit the digital beamforming part (open-loop solution). This implementation gives an upper-bound on the system's performance and capacity.

For the second implementation, the AP can transmit multiple spatial streams to each user, and each user can use two or more RF chains to transmit and receive. Here, we reuse the same implementation proposal for simulating SU-MIMO as we need to eliminate inter-stream interference among streams belonging to the same user. In addition, we need to reduce interference between users as the analog beams are not orthogonal. This implementation requires simulating the effect of digital beamforming. The overhead of this implementation increases with the number of users participating in the MU-MIMO communication.

3 CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed implementation for simulating SU/MU-MIMO communications in ns-3 for the next generation 60 GHz standard, IEEE 802.11ay. Our proposal introduces minimum signal processing blocks to improve both the accuracy and fidelity of SU/MU-MIMO simulations. We plan to implement our proposal together with the IEEE 802.11ay standard in ns-3. The next step is to evaluate the performance of our proposal against a link-level simulator that performs symbol level modeling.

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