ns-3 and 5G-LENA extensions to support MIMO

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ABSTRACT
MIMO spatial multiplexing is an essential feature to increase the communication data rates in current and future cellular systems. Currently, the ns-3 lte module leverages an abstraction model for 2×2 MIMO with spatial multiplexing of 2 streams; while mmWave and nr modules were lacking the spatial multiplexing option until this work, since the ns-3 models were not supporting the usage of multiple antennas for spatial multiplexing and an abstraction model such as the one used in the lte module is not suitable for the mmWave frequencies. In this paper, we propose, implement and evaluate a 2-stream MIMO spatial multiplexing models for ns-3 and the nr module. The proposed extension for the ns-3 supports multiple antennas for MIMO spatial multiplexing and can be used by any ns-3 module that is compatible with the ns-3 antenna array based models, such as nr and mmWave modules. We leverage this ns-3 extension to model 2-stream MIMO by exploiting dual-polarized antennas and their orthogonality under line-of-sight conditions, as it happens at high frequency bands, to send the two data streams. The proposed model does not rely on abstraction, as the MIMO model in the ns-3 lte module, and can thus model more realistically the propagation differences of the two streams, correlation, inter-stream interference, and allows design and evaluation of the rank adaptation algorithms. Additionally, we propose and evaluate an adaptive rank adaptation scheme and compare it with a fixed scheme. The developed MIMO spatial multiplexing models for the ns-3 simulator and the nr module are openly available.

CCS CONCEPTS
• Networks → Network simulations. Mobile networks.

KEYWORDS
ns-3, NR, MIMO, spatial multiplexing, dual-polarized antennas.

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1 INTRODUCTION
The use of multiple antennas in communication systems (a.k.a. Multiple-Input Multiple-Output (MIMO) systems) has attracted a lot of attention in the recent decades. MIMO permits [2]:

• increasing the data rate by sending multiple data streams simultaneously (known as spatial multiplexing), thanks to the use of various Radio Frequency (RF) chains,

At high carrier frequencies within the millimeter wave (mmWave) region, beamforming is particularly essential to combat the high pathloss propagation losses and blocking effects [14]. In case of beamforming, a single spatial stream is sent per receiver and the multiple antennas are used to concentrate the radiated power towards the receiver’s location, thus improving the received SINR and the probability of error at the target receiver, as well as reducing the generated interference towards other spatial locations. To further increase the user data rates, MIMO spatial multiplexing is required, to allow sending multiple data streams per user. However, mmWave systems may use only a small number of RF chains (and so, low number of spatial streams) due to the high cost and power utilization of RF chains working at high carrier frequencies.

In the literature, antenna polarization has been proposed as an attractive strategy to realize MIMO spatial multiplexing [15]. In particular, advanced polarization techniques such as dual-polarized antennas have been shown to improve the spectral efficiency of multiple antenna systems as compared to classical MIMO systems, for low levels of cross polarization discrimination [4]. Dual-polarized antennas are indeed a practical and effective way to enable MIMO spatial multiplexing at mmWave frequencies, because only two RF chains are needed, which is suitable for real implementations in those bands, and because propagation is characterized by low levels of cross polarization discrimination. Basically, in MIMO mmWave with dual-polarized antennas, two streams can be simultaneously sent across the two orthogonal polarizations (i.e., vertical (0) and horizontal (+90) polarizations, or +45 and −45 polarizations), as considered by 3GPP [1].

The ns-3 mmwave module for 5G NR in mmWave bands [11], as well as the ns-3 nr (5G-LENA) module for 5G NR in sub 6 and mmWave bands [12] support various ideal beamforming methods. Recently, we developed realistic beamforming methods [5], for which real resources are employed to perform beam management, considering a non-ideal channel estimation. However, both modules have been lacking up to now MIMO spatial multiplexing feature. In ns-3 lte (LENA) module there is an abstraction model to simulate 2×2 MIMO, which models up to two spatial streams per user. However, such a model does not account for propagation differences among different streams, and assumes no correlation between antennas, which is a non-realistic assumption for mmWave bands.

In this paper, relying on dual-polarized antennas, we propose, implement, and evaluate a 2-stream MIMO model for NR. The model is specifically suited for high frequency bands (i.e., mmWave), because it assumes the use of only two RF chains at gNB and UE nodes. Even
so, it can be also applied to sub 6 GHz bands without modifications, just with the inherent limitation of two spatial streams per user.

The rest of the paper is organized as follows. Sec. 2 reviews MIMO antecedent implementations in ns-3. Sec. 3 describes the adopted MIMO model for 5G NR at high frequency bands, which combines spatial multiplexing and beamforming. Sec. 4 presents the ns-3 implementation details of the proposed MIMO framework, including the changes in the antenna and the spectrum module, and the PHY and MAC layers of the nr module. Finally, Sec. 5 details the simulation example, and Sec. 6 presents the simulation results for validation.

2 MIMO ANTECEDENTS IN NS-3

The ns-3 lte module includes abstracted MIMO models for spatial multiplexing and transmit diversity [3]. The model is based on a statistical gain of several MIMO solutions with respect to the SISO (Single-Input Single-Output) one [6], assuming no correlation between the antennas. It supports various MIMO schemes, namely, SISO, MIMO-Alamouti, MIMO-MMSE, MIMO-OSIC-MMSE and MIMO-ZF schemes. In the case of MIMO spatial multiplexing, the PHY abstraction model is limited to 2 streams per UE. At the MAC layer, multiple MAC transport blocks are created, one per stream, and this is considered in the scheduler as well. The no correlated antennas assumption does not hold for mmWave bands, in which indeed the MIMO channel can be rank deficient, with correlated antenna elements. So, these models are not applicable there.

The ns-3 mmwave module [11] introduced various MIMO beamforming methods for mmWave bands. Namely, the long-term covariance matrix method, the beam search method and the line-of-sight (LOS) path method. In the long-term covariance matrix method, beamforming vectors are computed from the maximal eigenvectors of the channel covariance matrix. In the beam search method, it is assumed that there is a discrete number of beams from a pre-designed codebook, from which the beam that provides the largest SINR (considering the beam and the channel matrix) is selected for each gNB-UE link. In the LOS path method the DoA is assumed to be perfectly known and used to calculate the beamforming vectors to steer the beam towards such direction.

In the ns-3 nr module [12], we had available MIMO beamforming methods, as inherited from the mmwave module, i.e., the beam search method and the LOS path method. Later on, we introduced the representation for a quasi-omnidirectional beamforming, and multiple combinations with the previous methods (e.g., the gNB using beam search method and the UE using quasi-omni reception). Recently, we went a step over the ideal beamforming methods, and implemented realistic beamforming methods using SRS-based channel estimates [5]. That is, we used SRS (transmitted in specific time/frequency resources) to estimate the channel matrix, and then determine the beamforming vectors at the gNB based on the SRS-based channel estimate.

However, all the methods available in ns-3 NR modules (mmwave and nr) [5, 11, 12] up to date, were focusing on MIMO beamforming and they were missing the support of MIMO spatial multiplexing. With the contribution of this paper, we start to fill this gap.

3 MIMO MODELING FOR MMWAVE BANDS

3GPP considers gNB/UE nodes equipped with dual-polarized uniform planar antenna arrays [1]. In such systems, each array of antennas is divided evenly into two subarray groups with different polarizations (e.g., one subarray of vertically polarized antennas and the other subarray of horizontally polarized antennas). The gNB/UE have two RF chains, one for each polarization. In addition, assume that each antenna subarray (or polarization) is precoded with its own beamforming vector, to overcome mmWave propagation limits. This way, the MIMO model adopted in 5G-LENA, can combine spatial multiplexing (with up to two spatial streams per user) and beamforming (applied to each spatial streams separately).

Figure 1.(a) illustrates the cross-polarized antenna model considered in 3GPP [1]. The 3GPP model considers that in each panel, antenna elements are placed in the vertical and horizontal direction, where $N$ is the number of columns and $M$ is the number of antenna elements with the same polarization in each column. The antenna elements are uniformly spaced in the horizontal direction with a certain spacing and in the vertical direction with a certain spacing. The antenna panel can be either single polarized $(P = 1)$ or dual-polarized $(P = 2)$. In case of $P = 1$, all the antenna elements are vertically polarized (with polarization slant angle of 0). In case of $P = 2$, a subset of the antenna elements are polarized with polarization slant angle of $+45^\circ$ (red elements in the figure), and the rest with $-45^\circ$ (blue elements in the figure). Figure 1.(a) shows an example for $M = 2, N = 4$, and $P = 2$.

Figure 1.(b) shows how the dual-polarized antennas can be used for a transceiver design that supports MIMO spatial multiplexing. In this case, we have two RF chains, associated with two analog beamforming vectors, that connect to the antenna elements of a given polarization. Each spatial stream is associated to one of the polarizations. In the figure, stream 1 is sent/received through/by the $+45^\circ$ polarized antennas, and stream 2 is sent/received through/by the $-45^\circ$ polarized antennas.

Finally, Figure 2 shows the subarray partition concept, when applied to the 3GPP antenna array and the full MIMO model architecture for mmWave. Basically, antennas with same polarization are mapped to the same antenna subpartition, as shown in Figure 2.(a).
We extended the UniformPlanarArray class of antenna module to support multiple channel matrices among the same pair of nodes. The TX and RX nodes have multiple collocated antenna arrays, there are no models yet in ns-3 for channel modeling among the same pair of the TX and RX nodes. Additionally, each pair of the TX and RX antenna subarrays has a specific channel matrix and fading, which depends on the actual antenna element positions and field patterns of each pair of antenna array subpartitions.

For that reason, we split the function GetNewChannel into GetNewChannelParams and GetNewChannelMatrix, which update the respective parameters. Accordingly, the channel parameters are saved into two separate structures (ChannelParams - per node pair and ChannelMatrix - per phased antenna array pair). Figure 3 illustrates the main channel structures (a) before and (b) after the split. Grey color indicates the structures that existed before the split. Orange color denotes the existing structure but updated. Green color shows the two new structures, one generic, implemented in the base class MatrixBasedChannelModel, and its 3GPP specialization implemented in ThreeGppChannelModel class. Notice that, the previously existing structure called ThreeGppChannelMatrix does not exist anymore, instead, most of its fields have been moved to ThreeGppChannelParams structure.

Additionally, to allow multiple antenna arrays per device (and per SpectrumChannel instance), we extended the spectrum module to support passing the TX and RX antenna arrays objects to the spectrum propagation loss models that require pointers to TX and RX antenna array objects in order to calculate RX PSD, like e.g. ThreeGppSpectrumPropagationLossModel, which needs the beam-forming vectors to calculate RX PSD. To achieve this, we created a new type of spectrum propagation loss model interface called PhasedArraySpectrumPropagationLossModel, in which its function CalcRxPowerSpectralDensity has as input also the pointers to TX and RX antennaArray objects in order to calculate RX PSD. To achieve this, we created a new type of spectrum propagation loss model interface called PhasedArraySpectrumPropagationLossModel, in which its function CalcRxPowerSpectralDensity has as input also the pointers to PhasedArrayModel objects of the TX and RX. ThreeGppSpectrumPropagationLossModel class now inherits this new interface.

By adding this very simple design change into the spectrum module, we removed a hard limitation of ThreeGppSpectrumPropagationLossModel which was to support a maximum of 1 antenna array instance per ns-3 device (per SpectrumChannel instance). According to the new spectrum design, all devices that use antenna arrays and related spectrum models, should configure PhasedArray antennaArray per SpectrumPhy instance and attach the SpectrumPhy instance to the channel of interest. In this way, devices can have several antenna arrays transmitting and receiving on the same SpectrumChannel. Figure 4 illustrates these extensions.

In the MultiModelSpectrumChannel::StartTx function we added a condition that checks whether the TX/RX SpectrumPhy instances belong to the different nodes. This is needed to avoid pathloss calculations among the antenna arrays of the same node, because there are no models yet in ns-3 for channel modeling among the antenna arrays of the same node.

The proposed changes to spectrum module generalize the previous functionality, i.e., multiple antenna arrays are permitted per device and SpectrumChannel, while the behaviour when a single antenna array is configured remains the same. However, due to the changes related to ThreeGppSpectrumPropagationLossModel API, the modules that use this API need to override the function SpectrumPhy::GetAntenna to return the PhasedAntennaArray.

Figure 2: Subarray partition concept, applied to (a) dual-polarized antenna model in 3GPP and (b) MIMO model

The two subpartitions are collocated in space (see Figure 1), just here are separated in a logical manner. Our implementation in ns-3 follows this same concept. Based on the logical partitions, it is easy to associate spatial streams to subpartitions, as graphically illustrated in Figure 2.(b).

4 NS-3 AND NR IMPLEMENTATIONS FOR MIMO

This section provides the MIMO implementation details, including the ns-3 changes to support multiple antenna subarrays (in antenna and spectrum modules), and changes to the nr module to support MIMO spatial multiplexing (mostly in PHY and MAC layers).

4.1 ns-3 antenna

We extended the UniformPlanarArray class of antenna module, to consider the polarization slant angle. In particular, the attribute PolSlantAngle is the polarization slant angle that applies to all elements of a subarray partition. This value has to be configured separately for each subarray partition, e.g., with +45 for the first subarray partition and with −45 for the second subarray partition. This is already included in ns-3-dev.

4.2 ns-3 spectrum

The major changes to support the MIMO architecture for mmWave are introduced in the spectrum module. These changes aim at extending the current spectrum framework to support multiple array subpartitions per gNB/UE devices. To support such collocated antenna arrays (subpartitions) per device we needed to extend the ThreeGppChannelModel to be able to distinguish the channel parameters that are common for all the channels among the same pair of the transmit/receive (TX/RX) nodes and those that are specific for the TX/RX antenna subpartition array pair. For example, if the TX and RX nodes have multiple collocated antenna arrays, there will be multiple channel matrices among the same pair of nodes for the different pairs of the TX and RX antenna subarrays. However, these channel matrices that are among the same pair of nodes have common channel parameters, i.e., they share the same channel condition, cluster powers, cluster delays, AoD, AoA, ZoD, ZoA, K_factor, delay spread, etc. [1]. Hence, these parameters should not be regenerated for each pair of antenna subarrays among the same pair of the TX and RX nodes. Additionally, each pair of the TX and RX antenna subarrays has a specific channel matrix and fading, which depends on the actual antenna element positions and field patterns of each pair of antenna array subpartitions.

For that reason, we split the function GetNewChannel into GetNewChannelParams and GetNewChannelMatrix, which update the respective parameters. Accordingly, the channel parameters are saved into two separate structures (ChannelParams - per node pair and ChannelMatrix - per phased antenna array pair). Figure 3 illustrates the main channel structures (a) before and (b) after the split. Grey color indicates the structures that existed before the split. Orange color denotes the existing structure but updated. Green color shows the two new structures, one generic, implemented in the base class MatrixBasedChannelModel, and its 3GPP specialization implemented in ThreeGppChannelModel class. Notice that, the previously existing structure called ThreeGppChannelMatrix does not exist anymore, instead, most of its fields have been moved to ThreeGppChannelParams structure.

Additionally, to allow multiple antenna arrays per device (and per SpectrumChannel instance), we extended the spectrum module to support passing the TX and RX antenna arrays objects to the spectrum propagation loss models that require pointers to TX and RX antenna array objects in order to calculate RX PSD, like e.g. ThreeGppSpectrumPropagationLossModel, which needs the beam-forming vectors to calculate RX PSD. To achieve this, we created a new type of spectrum propagation loss model interface called PhasedArraySpectrumPropagationLossModel, in which its function CalcRxPowerSpectralDensity has as input also the pointers to PhasedArrayModel objects of the TX and RX. ThreeGppSpectrumPropagationLossModel class now inherits this new interface.

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The proposed changes to spectrum module generalize the previous functionality, i.e., multiple antenna arrays are permitted per device and SpectrumChannel, while the behaviour when a single antenna array is configured remains the same. However, due to the changes related to ThreeGppSpectrumPropagationLossModel API, the modules that use this API need to override the function SpectrumPhy::GetAnntenna to return the PhasedAntennaArray.
corresponding to that SpectrumPhy instance. Figure 4 shows that, e.g., NrSpectrumPhy inherits SpectrumPhy and implements this function. According to the proposed API, GetRxAntenna function returns a pointer to Object so that it can support two different types of antenna models in ns-3, i.e., those based on AntennaModel API as well as PhasedAntennaArray API.

The proposed spectrum module's extensions are valuable for ns-3 because by allowing multiple antenna arrays per device on the same SpectrumChannel, modules using this propagation model can be extended to support MIMO through dual-polarized antennas, i.e., as we explain in this paper on the example of the nr module. Also, this model can be used for MU-MIMO, by considering multiple subarrays to transmit streams towards different users through the array subpartition concept. Furthermore, it could enable the hybrid centralized RAN architecture, with a gNB node controlling multiple radio units.

4.3 ns-3 nr PHY

In the following, we describe the nr PHY layer extensions to support MIMO spatial multiplexing.
4.3.1 RI computation and rank adaptation algorithm. In real systems, a gNB capable of performing MIMO spatial multiplexing, e.g., in the Downlink (DL), can use more than one stream to transmit to those UEs that support MIMO spatial multiplexing. However, gNB’s decision to use multiple streams depends on the channel Rank Indicator (RI) reported by a UE. We implemented two schemes for computing the RI for DL MIMO transmissions: fixed and adaptive.

**Fixed RI scheme.** The fixed RI scheme uses a fixed RI configured by the user of the simulator. To enable this scheme, we added UseFixedRi and FixedRankIndicator attributes, in the NrUePhy class. For example, to use a fixed RI of 1 for a particular UE or all the UEs throughout the simulation, one can configure useFixedRi = true and FixedRankIndicator = 1. This configuration entails that irrespective of the UE’s support for MIMO (i.e., it has two subarrays), the gNB throughout the simulation will use only one stream (i.e., the first subarray) to transmit to the UEs reporting fixed RI of 1.

**Adaptive RI scheme.** The adaptive RI scheme uses an adaptive algorithm based on two SINR thresholds to compute an RI value [9]. We have considered two SINR thresholds to differ the case of transmission with better CQI for future allocations.

This algorithm compares the SINR of the data channel (i.e., PDSCH) of a single wide-band CQI value to a gNB under SISO communications, such as Singular Value Decomposition (SVD) on a channel matrix to compute the Rank of the channel. However, these matrix operations cannot be performed in ns-3 without the support of external libraries (if any). In addition, it could increase the simulation time that grows exponentially with the number of channel objects in a simulation. Therefore, we propose to use SINR to achieve a simple and less computationally complex RI adaptation algorithm(s).

This algorithm compares the SINR of the data channel (i.e., PDSCH) of each active stream for which UE has received the data with two preconfigured thresholds to determine the RI value (1 or 2). To enable this adaptive RI algorithm, one must set the NrUePhy attribute, UseFixedRi, to false. Moreover, these two SINR thresholds, namely, RiSinrThreshold1 and RiSinrThreshold2, are attributes of the NrUePhy class and can be configured as required. In detail, a UE that has the SINR of one active stream compares it with RiSinrThreshold1. If it is above this threshold, the UE has excellent propagation conditions, and it can report an RI value of 2 (i.e., switching from one to two streams). On the other hand, if a UE is already receiving data using two streams, it compares the SINR of each stream with RiSinrThreshold2. If the SINR of both the streams is above this threshold, it keeps reporting an RI value of 2; otherwise, it uses an RI value of 1 (i.e., switching from two streams to one). We note that when a UE switches from two streams to one, besides reporting an RI value of 1, it also reports the CQI of both the streams to the gNB. This allowed the extension of the scheduler to choose the stream with better CQI for future allocations.

4.3.2 CQI and RI reporting. NrUePhy already supports reporting of a single wide-band CQI value to a gNB under SISO communication. It uses a C++ structure DICqInfo that mimics the information element cqiListElement of FemtoForum MAC scheduler interface specifications [8]. However, with the introduction of MIMO, NrUePhy should communicate the CQI of each MIMO stream for which it has received the data. Therefore, we replaced the member variable of this structure used to store one CQI value with a C++ vector capable of holding the CQI of multiple streams. In particular, there is a direct mapping between a stream index and the indexes of this vector. For example, the CQI of the first stream is stored at the index 0 of this vector because the streams are indexed from zero in our simulator. Finally, the DICqInfo structure includes a variable m_ri specifically to report the RI value to the gNB.

4.3.3 nr PHY TX/RX through multiple streams. To support multiple streams, the NrPhy class is extended to aggregate multiple NrSpectrumPhy instances, and there is one PhasedAntennaArray for each NrSpectrumPhy instance. Each instance of PhasedAntennaArray class models a subpartition of the antenna array, and each subpartition is used for a specific stream. This is illustrated in Figure 5. To achieve the proposed MIMO spatial multiplexing configuration, we install two NrSpectrumPhy instances per NrGnbPhy and NrUePhy, and then we configure the two UniformPlanarArray instances, two antenna array subpartitions, belonging to the same NrGnbPhy or NrUePhy to be cross polarized. For this, the extension of the ns-3 UniformPlanarArray is used, described in Sec. 4.1. Even if there are 2 subpartitions of cross polarized antenna arrays at both gNB and UE, with the current implementation, both streams will be used for the DATA/CTRL transmission only in the DL. The Uplink (UL) is configured to use a single stream for CTRL and DATA, while SRS is transmitted in both streams in UL to allow the realistic beamforming functionality.

4.3.4 Beamforming per antenna subpartition. To support the beamforming per subpartition of antenna array, we changed the NR PHY model to have a BeamManager per NrSpectrumPhy, instead of having a single BeamManager per NrUePhy or NrGnbPhy. This was necessary because one BeamManager instance supports a single beamforming vector configuration (hence single subpartition). Additionally, the whole NR module’s beamforming framework, including ideal and realistic algorithms, and corresponding helpers, we extended to support multiple antenna arrays or subpartitions per NrUePhy or NrGnbPhy instance, that the beamforming is performed independently per each subpartition. Beamforming functionality in nr module assumes that the beamforming should be performed among the subpartitions with the same index, i.e., the beamforming is performed among the 1st subarray of the gNB and the 1st subarray of the UE, and among the 2nd subarray of the gNB and 2nd subarray of the UE. If a gNB supports 2 streams, and a UE only 1 stream, the beamforming is done among the 1st subarray of the gNB and the UE’s subarray. Also, since SRS is reported
per each stream, NR module’s realistic beamforming is updated to be performed per each stream. Figure 5 illustrates the nr module beamforming model support for MIMO.

### 4.3.5 HARQ and SINR reporting for multiple streams

The nr PHY model, including NrSpectrumPhy and NrUePhy, is extended to support Hybrid Automatic Repeat Request (HARQ) and SINR reporting for multiple streams. The nr PHY functions are extended to include the index of the stream when e.g., HARQ is reported, and the index is used to merge the feedbacks from different streams into the new HARQ structure. Similarly, SINR reporting is updated to support multiple streams, i.e., when NrSpectrumPhy notifies NrUePhy about SINR, it indicates to which streams this SINR corresponds. Previously, all the interference traces were hooked to NrUePhy, because there was only 1 NrSpectrumPhy per NrUePhy. But, since now we may have multiple NrSpectrumPhy instances per NrUePhy, we connect the SINR traces coming from NrInterference and ChunkProcessors directly to NrSpectrumPhy, and then NrSpectrumPhy passes these traces to NrUePhy by indicating also the stream to which corresponds the trace.

### 4.3.6 TX power per stream

When setting the gNB transmit power for each transmission, it is taken into account that the configured power is the total power of all active streams of that NrGnbPhy. So, the transmit power per stream is being dynamically determined before each transmission and depends on the number of the active streams, i.e., the total transmit power is divided by the number of the active streams.

### 4.3.7 Inter-stream interference

Another important aspect we studied is how to handle inter-stream interference. We implemented two different ways to configure and tune inter-stream interference. First, we implemented a new channel model called ThreeGppChannelModel, based on ThreeGppChannelModel, with which we can parametrize the inter-stream interference correlation, based on the 3GPP cross-polarization correlation parameter. Secondly, we added in NrSpectrumPhy an attribute called InterStreamInterferenceRatio which can tune the level of the inter-stream interference, and it depends on the assumed receiver’s capability to handle this interference. The value of this parameter ranges from 0 to 1.0 value means that there is no inter-stream interference, and 1 that the full inter-stream interference is taken into account, i.e., the RX PSD of the cross-polarized signal is considered when SINR is calculated. For example, we observed when assuming full inter-stream interference (InterStreamInterferenceRatio = 1) that in scenarios of no cross-polarization correlation (i.e., ThreeGppChannelModelParam configured in a such way that there is no correlation among the streams of different polarizations), the inter-stream interference goes to 0, while in other scenarios, interference is present.

### 4.3.8 Support for OFDMA scheduling

In the nr module the OFDMA scheduling has the constraint that at the same variable TTI can be served simultaneously the UEs for which a gNB uses the same beam. To be able to distinguish among available beams, the nr module was relying on the concept of Beamld, which uniquely identifies a beam [13]. In order to support the OFDMA scheduling with MIMO spatial multiplexing while avoiding invasive changes of the OFDMA schedulers code, we created a BeamConfId structure based on Beamld, which identifies uniquely the pair of beams (one for each stream). In this way, only the UEs for which a gNB uses exactly the same “beam configuration” (BeamConfId), can be scheduled at the same time in the OFDMA manner. This implementation takes into account that some UEs can, in general, support a variable number of streams (1 or 2). Most of the nr extensions explained in this paper could support any number of streams, except the code for the OFDMA scheduling which depends on BeamConfId and thus supports up to two streams. Once in the future when this limitation is removed, the nr extensions for MIMO proposed in this paper will support any number of streams.

### 4.4 ns-3 nr MAC

One of our main objectives while designing an nr module’s support for MIMO spatial multiplexing was to keep intact the original SISO functionality. As a result, the proposed extension does not affect the core functionality of the MAC layer, nor the existing schedulers (e.g., RR, PF, and MR). To support the MAC scheduling of two transport blocks (one for each stream), we extended classes responsible for the core MAC functionalities, e.g., CQI management, DL Control Information (DCI) creation, HARQ feedback processing, etc. In the following, we explain these extensions.

#### 4.4.1 CQI management

In the nr module, the class NrMacSchedulerCQIManagement is the final destination for DL and UL CQI reports. One of the main purposes of this class is to compute the DL and UL Modulation and Coding Scheme (MCS) based on their respective CQIs. Since the MIMO support is introduced only for DL, the function DlWBCQIReported has been updated to read the new DL CQIInfo structure. Based on the CQI of each stream, it computes their MCS that is later used for deducing a TB size in NrMacSchedulerUeInfo::UpdateDLMetric.

#### 4.4.2 DCI creation

The NR module supports dynamic scheduled-based access both for DL and UL [13]. A gNB is responsible for conveying the scheduling information (i.e., DL or UL) using a DCI to its UEs. A C++ struct, VarTtiAllocInfo, is currently used to communicate all the scheduling-related information needed by a gNB and a UE to orchestrate their transmissions and receptions. VarTtiAllocInfo structure contains: 1) DciInfoElementTdma structure, which represents the DCI, and 2) RlcPduInfo, which carries the number of bytes assigned to each active logical channels. Both structures
were supporting originally the scheduling information for only one stream or TB. Therefore, to support multiple streams, we extended both, as shown in Fig. 6. In DciInfoElementTdma, we extended the TB-related information variables, such as MCS, New Data Indicator (NDI), Redundancy Version (RV), and the TB size to be per stream or TB. We use a C++ vector for holding the TB-related information for each stream to allow that scheduler can simultaneously schedule the TBs of multiple MIMO streams. Similarly, to maintain the RlcPduInfo per MIMO stream, we wrapped the existing vector of RlcPduInfo into another vector per stream. The indexes of these vectors are analogous to the stream indexes at the nr PHY layer.

4.4.3 MAC scheduling. Thanks to the PHY layer extensions for MIMO, the CQI is reported per each stream. Hence, the scheduling of the new data is independent among the two streams and is performed by using the MCS of a specific stream. Also, the TB size may differ between the two streams. This is a much more realistic behaviour than the one assumed in the current LTE’s module abstraction model for MIMO. Also, if the CQIs are different between the two streams it may happen that a UE would be able to decode only one TB, which means that the NDI and RV information would not be the same for the two streams. Hence, the subsequent retransmissions (if any) are also independent.

The number of streams to be used by the MAC scheduler for a specific UE depends on the RI value reported by the UE in a DL CQI report. In case that a UE reports an RI = 1 (e.g., due to bad channel conditions), the proposed nr rank adaptation model is robust enough to choose a stream with a better CQI to schedule. In contrast to having a fixed RI value, the scheduler can adaptively choose the number of streams to use.

(1) At the beginning of a simulation when the scheduler uses only one stream that belongs to the first subarray, even for the UE(s) that can support MIMO. This design choice is motivated by the two facts:
(a) The current RRC model does not support UeCapabilityReport through which UE communicates its capability to support MIMO to a gNB, as in the standard.
(b) In the nr module, CQI is computed using the data channel. Hence, a gNB should schedule at least one TB to receive an RI value reported in the CQI report, on which it can decide whether to use one or two streams for the subsequent transmission(s).

(2) During the retransmission phase. Specifically, the scheduler keeps rescheduling the TB of each stream independently until a UE can decode both streams or the maximum number of retransmissions (i.e., RV = 3) has been reached.

4.4.4 HARQ feedback processing. The scheduler in the NR module is responsible for embedding a unique HARQ process id in every DCI it creates, and this functionality remains the same in the MIMO extension. Specifically, the simulator schedules multiple streams using a single DCI; thus, the same HARQ process id is used for all of them. It is worth mentioning that this implementation choice is aligned with the 3GPP standard. In particular, in the DCI format 1-1, which is a commonly used DCI for DL in NR, unlike TB-related information, the HARQ process id field is not repeated for each stream while using MIMO spatial multiplexing [7]. Moreover, similar to a real network, a UE in our simulator reports HARQ feedback (i.e., ACK or NACK) for each stream since it decodes them independently. To do that, we modified the C++ struct DHarqInfo, which is used to report the HARQ feedback in downlink following the Femto forum MAC API [8]. Specifically, this modification replaces the simple C++ enumeration (that represents ACK or NACK) with a vector of such enumeration so that a UE can report the HARQ feedback for the TB of each stream to its serving gNB.

At the gNB side, a HARQ feedback (i.e., DHarqInfo struct) from a UE is forwarded to the NrmacSignalling class for processing. In particular, we extended the ProcessHarqFeedback function of this class to read the HARQ feedback of each stream. Upon processing a HARQ feedback, if a UE has reported ACK for both streams’ TB, the HARQ process id is released, i.e., it can be reassigned to a new DCI. However, it may happen that a UE is able to decode the TB of only one stream, i.e., it reports ACK for one stream and NACK for the other. In this case, while processing the feedback, the scheduler will not release the HARQ process id and reschedules the TB of the failed stream using the same HARQ process id. Moreover, the scheduler will prioritize retransmission of the TB of this single stream over scheduling new data during such retransmission. It will keep scheduling only one stream (for which it received NACK) until the TB is successfully decoded or the maximum number of retransmissions is reached.

5 EXAMPLE

We created the cttc-nr-mimo-demo.cc example in the nr module to demonstrate the usage of the proposed MIMO framework. The topology consists of a single gNB and single UE. Simulation allows to configure various parameters, such as: the distance, the type of the RI value computation used (fixed or adaptive), the value of RI if fixed RI is used (1 or 2), the SINR thresholds if adaptive RI algorithm is used (see description in Sec. 4.3), the random run number (to run multiple simulations and average the results), the 3GPP scenario, and the MCS table. The traffic used in the example is the downlink UDP constant bit rate (CBR). The output of the example, such as TX/RX bytes, throughput, mean jitter, and mean delay, is shown on the terminal and is written to a text file.

6 SIMULATION RESULTS

For the evaluation, we use ns3 5G-LENA [12] with the 3GPP spatial channel model developed in [16], compliant with TR 38.901, but extended to account for dual-polarized antennas, and the NR-based PHY abstraction model described in [10]. The script used for evaluation is cttc-nr-mimo-demo.cc, explained in Sec. 5.

The scenario consists of 1 gNB and 1 UE, placed at a certain distance. The propagation condition follows the Urban Micro (UMi) scenario, as per TR 38.901 [1]. UMi is characterized by a gNB antenna height of 10 m, with a gNB transmit power of 30 dBm, and the UE has an antenna height of 1.5 m. The transmission is performed in the 3.5 GHz band region, using numerology 0 (i.e., 15 kHz subcarrier spacing), with 20 MHz channel bandwidth and a PRB overhead of 0.04 (typical of NR). The antenna array configuration consists of 2 × 2 dual-polarized directional antenna array at the gNB (i.e., the gNB has a total of 8 antenna elements) and 1 × 1 dual-polarized
We compare fixed RI scheme (RI equal to 1 or 2) and adaptive RI with MCS Table 2, 20 MHz channel bandwidth and numerology 0, when increasing the distance. So, the multiplexing gain is properly the 5G-LENA module to support MIMO spatial multiplexing with

In this paper, we presented an extension of the ns-3 simulator and the 5G-LENA module to support MIMO spatial multiplexing with dual-polarized antennas to send two streams. The developed model in the 5G-LENA exploits dual-polarized antennas to send two streams. The extension has implied major implementation changes in PHY and MAC layers of the nr module, as well as significant extensions in the ns-3 spectrum and antenna modules. We described the implementation changes and design choices in detail. Finally, we validated the proposed MIMO spatial multiplexing model in an Urban Micro scenario, for various gNB-UE distances, under a fixed rank (of 1 and 2) and the proposed rank adaptation algorithm.

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7 CONCLUSIONS
In this paper, we presented an extension of the ns-3 simulator and the 5G-LENA module to support MIMO spatial multiplexing with