www.cttc.es

5G-LENA NR MODULE OVERVIEW

04/06/2024, WNS3 2024

BILJANA BOJOVIĆ

Senior Researcher

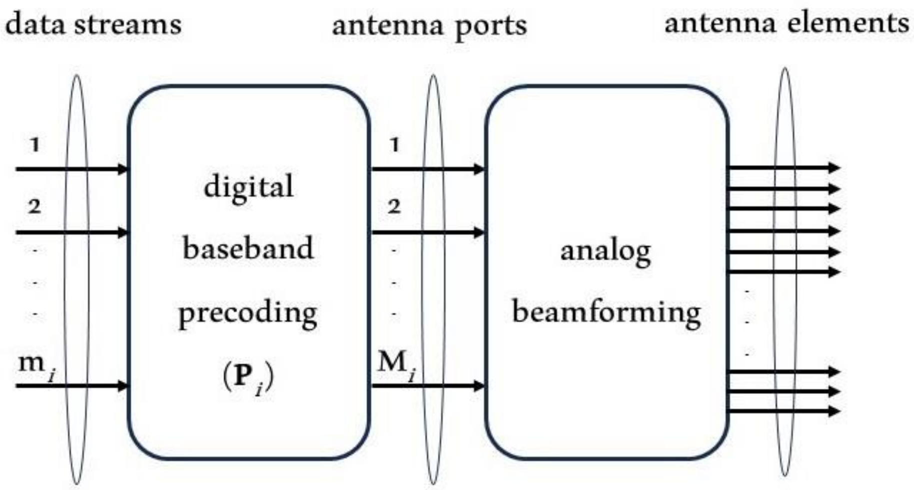
OpenSim Research Unit at CTTC

Spain

Centre Tecnològic de Telecomunicacions de Catalunya

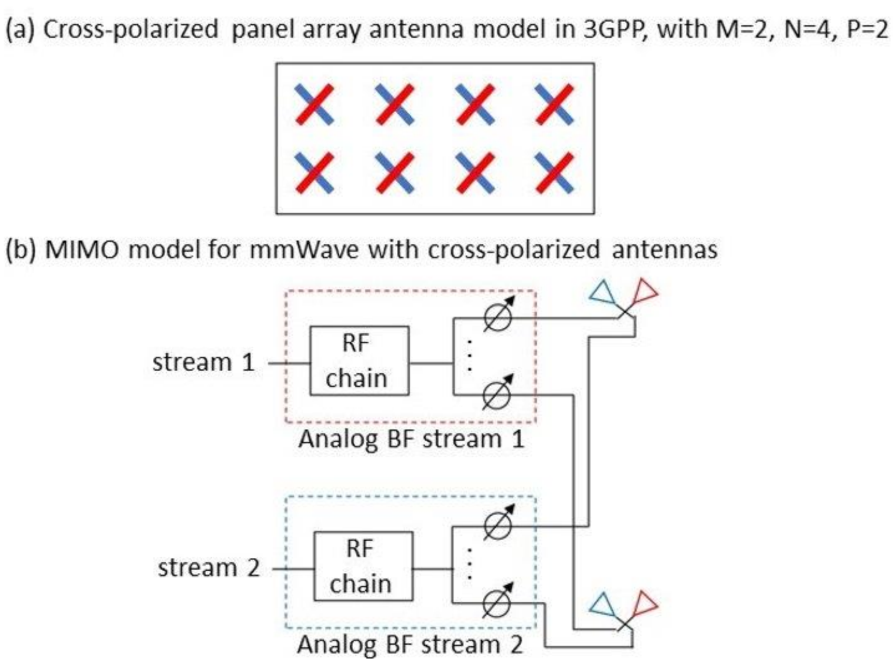
INRODUCTION

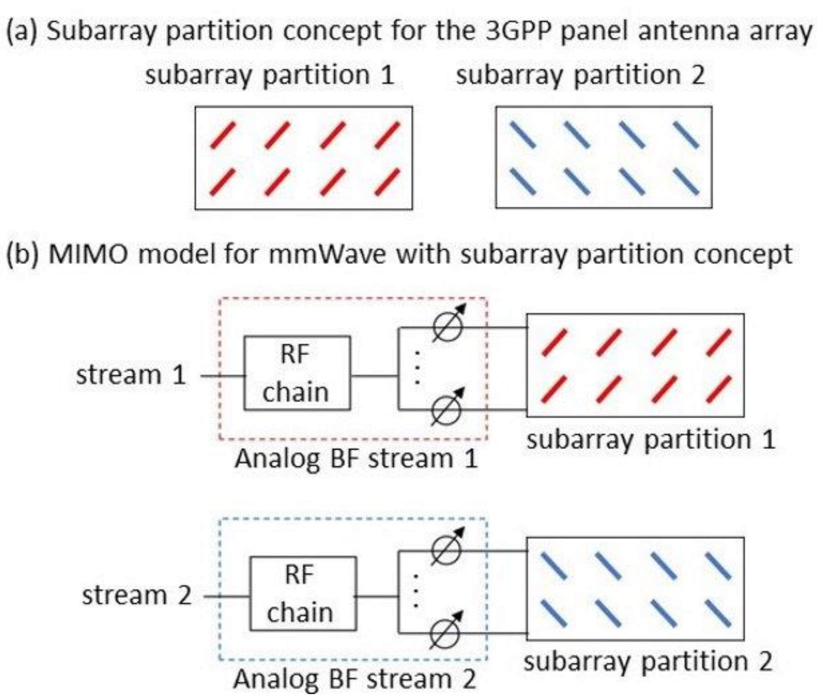
- Hybrid beamforming, combining digital and analog processing, is particularly promising for 5G New Radio (NR) and future networks
- 3GPP has adopted hybrid beamforming in 5G NR utilizing antenna ports for mapping data streams to antenna elements: supporting either sub-connected or fully connected architecture



NR PHY: SU-MIMO (OLD IMPLEMENTATION)

- Dual-Polarized MIMO model was supported, exploiting dual-polarized antennas, under line-of-sight conditions: Up to 2 streams per user, rank indicator reporting and rank adaptation algorithms





*B. Bojovic, Z. Ali, S. Lagen, **ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO**, in Workshop on ns-3, June 2022.*

INRODUCTION

- 3GPP employs codebook-based precoding with closed-loop MIMO, where Channel State Information (CSI) is fed back to the base station
- Network simulators like ns-3 are crucial for analyzing complex network setups, but to do so it is important to have an accurate physical layer modeling
- 5G-LENA has been supporting analog beamforming and DP-MIMO (limited and lacks 3GPP compliance)

3GPP SU-MIMO

- gNB uses a precoding matrix to align signals with the channel, i.e., the precoding matrix maximizing Signal-to-Interference-plus-Noise Ratio (SINR) is selected
- UE uses a receive filter to suppress interference and recover streams. The MMSE-IRC receiver is used for its performance and complexity balance
- 3GPP closed-loop MIMO is enabled by CSI feedback, which includes the PMI, RI, and CQI
- The UE selects the optimal precoding matrix and reports it via PMI from a predefined codebook
- The RI indicates the number of streams for the gNB to use
- Each antenna port aggregates multiple elements for digital precoding, with analog beamforming applied to elements within one port

SU-MIMO MODEL FOR 5G-LENA

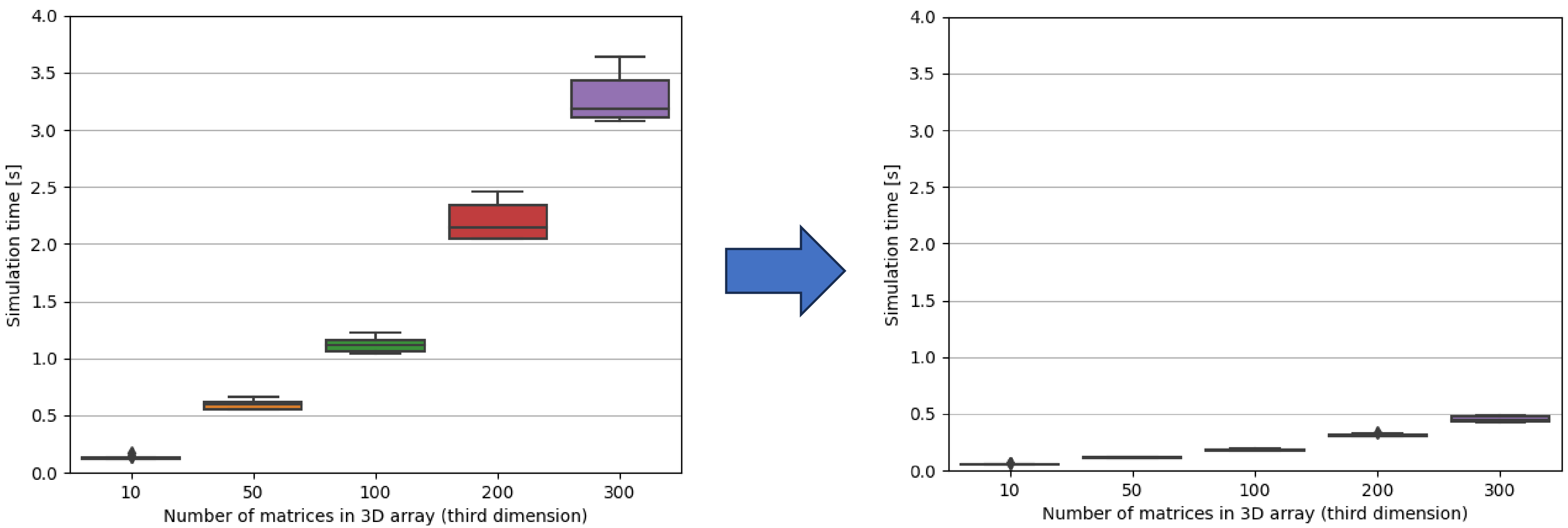
- The new 3GPP-compliant SU-MIMO model for ns-3 5G-LENA combines spatial multiplexing (up to 4 streams per user) and beamforming (up to 32 antenna ports) in both analog and digital domains
- It follows the 3GPP Type-I codebook-based precoding model with an MMSE-IRC receiver
- CSI feedback is extended to include PMI and RI along the CQI
- According to Type-I codebooks the precoding matrix W = W1 * W2
  - W1 represents wideband, long-term precoding, directs beams
  - W2 subband, frequency-dependent precoding, applies phase shifts over the polarizations
- An exhaustive search is used for precoding and rank (PMI/RI) selection

SU-MIMO MODEL FOR 5G-LENA

- Multiple streams are encoded in the same transport block (TB)
- SINR and interference computations are correctly modeled, enabling the reuse of the existing SISO error model for MIMO error modeling by vectorizing the 2D SINR into 1D SINR
- The model supports a standard-compliant closed-loop SU-MIMO mechanism
- CSI computation based on PDSCH reception
- To enable SU-MIMO we extended the ns-3 simulator and the nr module

SU-MIMO NS-3 EXTENSIONS

- ns-3 enhancements include:
  - Computational improvements for MIMO (Release 38):
    - Valarray and MatrixArray
  - 3GPP channel and antenna model support for multiple antenna ports and dual-polarized antennas (Release 41)



Previous ns-3 3D data structure

ns-3::MatrixArray

SU-MIMO NS-3 EXTENSIONS

- 3GPP channel and antenna model support for multiple antenna ports and dual-polarized antennas (Release 41)
  - The ns-3 uniform planar array extended to support multiple antenna ports and dual-polarized antennas
  - The sub-array partition model for TXRU virtualization
  - The ns-3 3GPP channel model is extended to include spectrum channel matrix
  - The precoding matrix per subband is introduced to support correct MIMO computations of the received signal and interference

SU-MIMO 5G-LENA MODULE EXTENSIONS

- Extensions:
  - Generalizing the OFDMA model to support MIMO
  - Interference modeling for MIMO SINR calculations
  - Computing SU-MIMO transport block error rate
  - 3GPP-compliant Type-I precoding codebooks
  - Optimal precoding search algorithm
  - Closed-loop MIMO with expanded CSI feedback
- Releases:
  - 5G-LENA 3.0 -> Two-port codebook
  - 32-port codebook and 4 streams soon to be released

GENERALIZING OFDMA FOR SU-MIMO

- The 5G-LENA module was initially designed with TDMA
- A technique called ``OFDMA downlink trick" combines multiple simultaneous transmissions into a single one
- The signal is created as a combination of allocations towards different UEs towards which gNB uses the same analog beam
- Challenging for SU-MIMO design, i.e., gNB may need to transmit to various UEs using different rank
- We generalized the OFDMA model to use a unique signal representation for each UE:
    - gNB may transmit to each UE by using different ranks, and
    - different digital beams can be used through digital processing which is designed per UE and can vary across RBs

MIMO INTERFERENCE

- The interference-plus-noise covariance matrix of the received signal is computed
- The received signal is transformed into an equivalent representation where the interference-plus-noise covariance is an identity matrix (a.k.a., interference whitening transformation)
- The SINR of each stream is computed based on the interference normalized channel and the precoding matrix
- The MIMO interference and SINR calculations require Eigen3, a C++ template library for linear algebra: matrices, vectors, numerical solvers, and related algorithms

SU-MIMO TBLER

- New functions to determine if a transport block was received successfully
- In the proposed model, a simple weighted average is performed over multiple different signal values received over time to get a single SINR matrix
- As the SINR and interference computations are correctly modeled, and multiple streams are fit into one TB, this allows reusing the existing SISO error model for MIMO error modeling
- The 2D SU-MIMO SINR matrix (of dimensions number of RBs, rank) is linearized into a 1D SINR vector (of dimensions number of RBs x rank, 1) and passed to the existing error model for SISO to obtain TBLER

3GPP TYPE-I CODEBOOKS

- We implemented the two-port and 32-port codebook according to Type-I Single-Panel Codebook 3GPP TS 38.214
- The 32-port codebook supports:
  - up to 32 antenna ports
  - codebook mode 1 only
  - the rank is limited to 4
- The precoding is defined by two indices i1 and i2
  - i1 is the composite index of wideband precoding, composed of i11, i12, and i13 indices (the horizontal, the vertical beam directions, and co-phasing shifts for the wideband precoding)
  - I2 is the subband precoding index

3GPP TYPE-I CODEBOOKS

- Codebook mode 1 means the per-subband i2 beam index is used only for the phase shift of the second polarization,
- To create different precoding matrices, different combinations of i11, i12, i13, and i2 indices are used

EXHAUSTIVE PMI/RI SEARCH

Algorithm 1 Exhaustive PMI/RI search

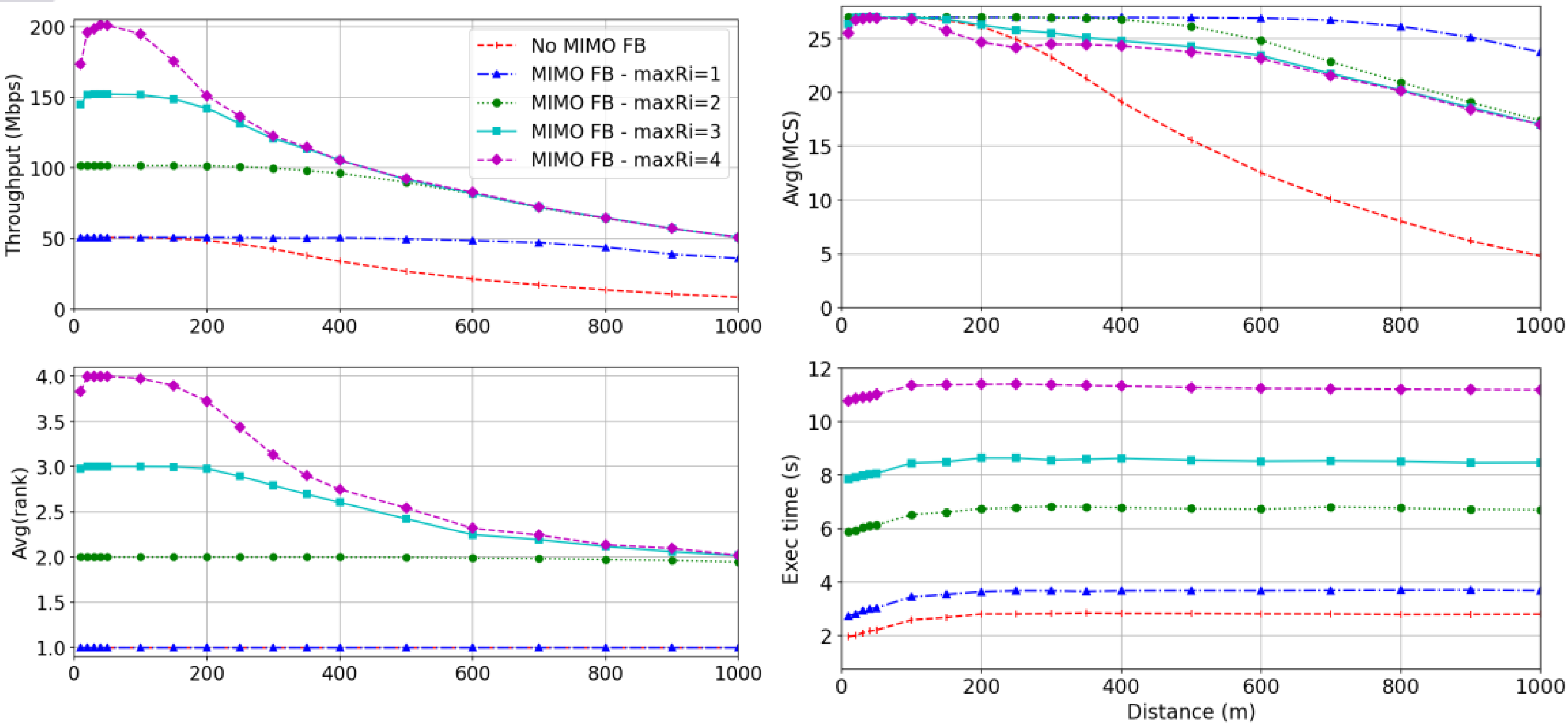
input: Interference-normalized channel matrix per subband $\bar{\mathbf{H}}_s$
for $< each\ r \in R >$ **do**
  for $< each\ i1 \in I1 >$ **do**
    for $< each\ s \in S >$ **do**
      for $< each\ i2 \in I2 >$ **do**
        $C^{\text{sb}}_{r,i1,s,i2} \leftarrow ComputeSbCap(\bar{\mathbf{H}}_s, \mathbf{W}_{i1,i2,r})$
        if $C^{\text{sb}}_{r,i1,s,i2} > C^{\text{sb}}_{r,i1,s,best\_i2(s)_{r,i1}}$ **then**
          $C^{\text{sb}}_{r,i1,s,best\_i2(s)_{r,i1}} \leftarrow C^{\text{sb}}_{r,i1,s,i2}$
          $best\_i2(s)_{r,i1} \leftarrow i2$
        end if
      end for
      $C^{\text{wb}}_{r,i1} = C^{\text{wb}}_{r,i1} + C^{\text{sb}}_{r,i1,s,best\_i2(s)_{r,i1}}$
    end for
    if $C^{\text{wb}}_{r,i1} > C^{\text{wb}}_{r,best\_i1_r}$ **then**
      $C^{\text{wb}}_{r,best\_i1_r} \leftarrow C^{\text{wb}}_{r,i1}$
      $best\_i1_r \leftarrow i1$
    end if
  end for
  if $C^{\text{wb}}_{r,best\_i1_r} > C^{\text{wb}}_{best\_r,best\_i1_r}$ **then**
    $C^{\text{wb}}_{best\_r,best\_i1_r} \leftarrow C^{\text{wb}}_{r,best\_i1_r}$
    $best\_r \leftarrow r$
    $best\_i1 \leftarrow best\_i1_r$
    $best\_i2(s) \leftarrow best\_i2(s)_{r,best\_i1_r}$
  end if
end for
output: best_r, best_i1, best_i2(s)

CLOSED-LOOP MECHANISM AND CSI FEEDBACK

- CSI computation is performed upon PDSCH reception
  - When PDSCH is received at UE, the CSI is computed at the UE
  - The CSI feedback message containing the optimal precoding matrix, the rank, and CQI is sent to the gNB
  - When gNB receives the CSI feedback, it uses the reported RI and CQI for the MAC scheduling and the precoding matrix per subband to perform the digital precoding
  - Once the UE receives the PDSCH, it also receives the precoding matrix
- Entire precoding matrix in the feedback message and not only its index (support for non-codebook-based precoding)

CLOSED-LOOP MECHANISM AND CSI FEEDBACK

- cttc-nr-mimo-demo based campaign (different distances, rank limits)



CTTC-NR-MIMO DEMO EXAMPLE

./ns3 run cttc-nr-demo

```
[0/2] Re-checking globbed directories...
ninja: no work to do.
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 15000
  Tx Bytes:   15420000
  TxOffered:  205.600000 Mbps
  Rx Bytes:   7592808
  Throughput: 101.237440 Mbps
  Mean delay:  157.787694 ms
  Mean jitter:  0.113485 ms
  Rx Packets: 7386


  Mean flow throughput: 101.237440
  Mean flow delay: 157.787694
 Mean rank: 2.000000
 Mean MCS: 26.919598
```

CTTC-NR-MIMO DEMO EXAMPLE

./ns3 run cttc-nr-mimo-demo -- --enableMimoFeedback=0

```
[0/2] Re-checking globbed directories...
ninja: no work to do.
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 15000
  Tx Bytes:   15420000
  TxOffered:  205.600000 Mbps
  Rx Bytes:   3808740
  Throughput: 50.783200 Mbps
  Mean delay:  230.372893 ms
  Mean jitter:  0.186494 ms
  Rx Packets: 3705


  Mean flow throughput: 50.783200
  Mean flow delay: 230.372893
 Mean rank: 1.000000
 Mean MCS: 27.000000
```

CTTC-NR-MIMO DEMO EXAMPLE

./ns3 run cttc-nr-mimo-demo -- --enableMimoFeedback=1 --rankLimit=1

```
[0/2] Re-checking globbed directories...
ninja: no work to do.
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 15000
  Tx Bytes:   15420000
  TxOffered:  205.600000 Mbps
  Rx Bytes:   3808740
  Throughput: 50.783200 Mbps
  Mean delay:  230.372893 ms
  Mean jitter:  0.186494 ms
  Rx Packets: 3705


  Mean flow throughput: 50.783200
  Mean flow delay: 230.372893
 Mean rank: 1.000000
 Mean MCS: 27.000000
```

CTTC-NR-MIMO DEMO EXAMPLE

./ns3 run cttc-nr-mimo-demo -- --enableMimoFeedback=0 --gnbUeDistance=400

```
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 15000
  Tx Bytes:   15420000
  TxOffered:  205.600000 Mbps
  Rx Bytes:   3256704
  Throughput: 43.422720 Mbps
  Mean delay:  236.689803 ms
  Mean jitter:  0.211604 ms
  Rx Packets: 3168


  Mean flow throughput: 43.422720
  Mean flow delay: 236.689803
 Mean rank: 1.000000
 Mean MCS: 23.688442
```

CTTC-NR-MIMO DEMO EXAMPLE

./ns3 run cttc-nr-mimo-demo -- --enableMimoFeedback=1 --rankLimit=1 --gnbUeDistance=400

```
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
  Tx Packets: 15000
  Tx Bytes:   15420000
  TxOffered:  205.600000 Mbps
  Rx Bytes:   3565104
  Throughput: 47.534720 Mbps
  Mean delay:  250.488728 ms
  Mean jitter:  0.199146 ms
  Rx Packets: 3468


  Mean flow throughput: 47.534720
  Mean flow delay: 250.488728
 Mean rank: 1.000000
 Mean MCS: 26.720268
```

CTTC-NR-MIMO-DEMO EXAMPLE 32-PORT CODEBOOK, UP TO 4 STREAM

- 32 port codebok cttc-nr-mimo-demo configurations comparison

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --fullSearchCb=ns3::NrCbTypeOneSp --enableMimoFeedback=0 --rankLimit=1

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --fullSearchCb=ns3::NrCbTypeOneSp --enableMimoFeedback=1 --rankLimit=1

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --fullSearchCb=ns3::NrCbTypeOneSp --enableMimoFeedback=1 --rankLimit=2

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --fullSearchCb=ns3::NrCbTypeOneSp --enableMimoFeedback=1 --rankLimit=3

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --fullSearchCb=ns3::NrCbTypeOneSp --enableMimoFeedback=1 --rankLimit=4

CTTC-NR-MIMO-DEMO EXAMPLE 32-PORT CODEBOOK, UP TO 4 STREAM

Change distance:

./ns3 run cttc-nr-mimo-demo -- --numColumnsGnb=2 --numRowsGnb=4 --numHPortsGnb=2 --numVPortsGnb=2 --xPolGnb=1 --numColumnsUe=2 --numRowsUe=1 --numHPortsUe=2 --numVPortsUe=1 --xPolUe=1 --enableMimoFeedback=0 --rankLimit=1 --fullSearchCb=ns3::NrCbTypeOneSp --gnbUeDistance=400

COMPUTATIONAL COMPLEXITY ISSUES

Problems:

- PMI/RI selection algorithm -> exhaustive algorithm, search space scales with the number of ports
- Generalizing OFDMA: More signals entering into the channel
- CSI-RS implementation-> We can reduce the number of the signals being processed at NrSpectrumPhy, but introducing new periodical signals

Solutions:

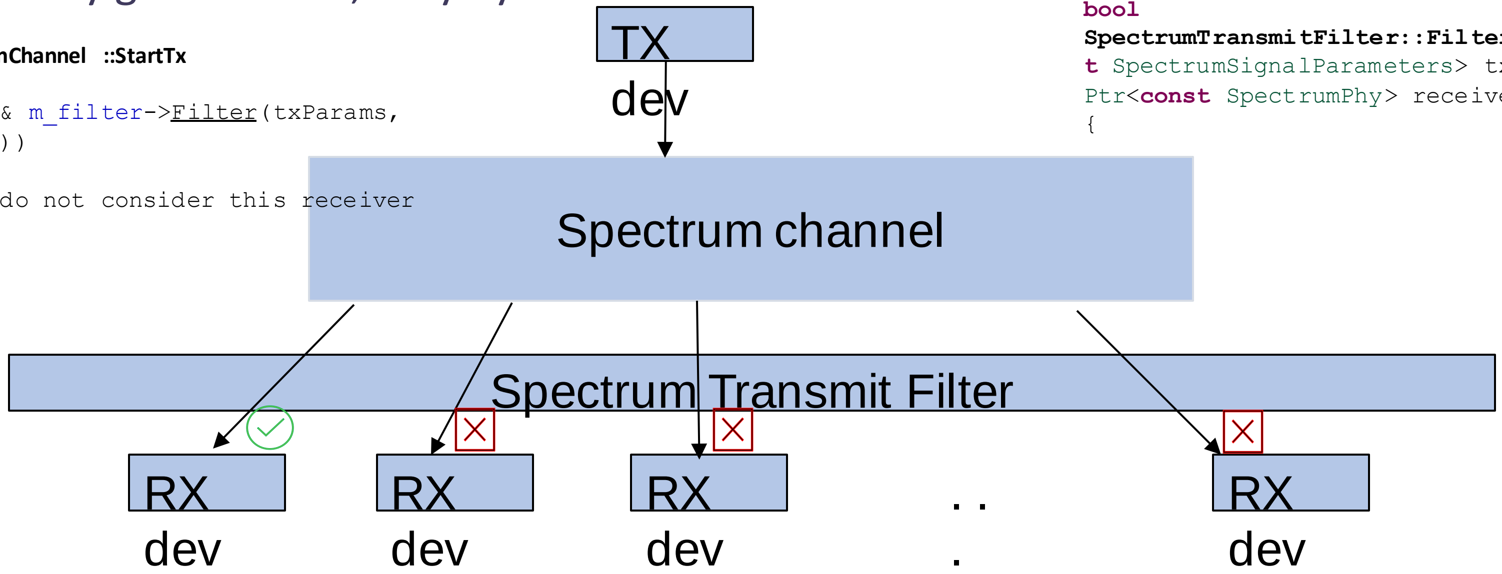
- Ideal PMI/RI search, sub-sampling or more efficient algorithms
- Signals can be filtered out by using spectrum filter: e.g., CSI-RS based on cellId +RNTI, or cellId

NS-3 SPECTRUM TRANSMIT FILTER

- Transmission of CSI-RS signal can impose a significant bargain for the already heavy PHY processing
- Use the ns-3:: SpectrumTransmitFilter is to prevent that the devices that do not need to process CSI-RS signal do it, e.g., CSI-RS should not be processed by gNB devices, only by UEs

MultiModelSpectrumChannel ::StartTx

```
...
if (m_filter && m_filter->Filter(txParams,
*rxPhyIterator))
{
continue;  // do not consider this receiver
}
...
```




```
bool
SpectrumTransmitFilter::Filter(Ptr<cons
t SpectrumSignalParameters> txParams,
Ptr<const SpectrumPhy> receiverPhy)
{
```

Advanced research for everyday life

tecnio catalonia

ACCIÓ

Generalitat de Catalunya

Fins a 31/12/2023

AENOR

Gestión I+D+i

UNE 166002

IDI-0024/2011

HR EXCELLENCE IN RESEARCH