Realistic Beamforming Design using SRS-based Channel Estimate for ns-3 5G-LENA Module

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Beamforming

What is it?

Beamforming (BF) is a key procedure to overcome propagation limits in millimeter-wave bands but also to extend network coverage in sub 6 GHz bands (by supporting MIMO).

How it works?

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 receiver, as well as reducing the interference towards other devices.

Which recent technologies employ beamforming?

Many recent communication standards, various IEEE 802.11 standards, such as, IEEE 802.11ax/ac/ad/ay, and 3GPP, such as 4G LTE (in transmission mode 7) and 5G NR.

Beamforming simulation models in ns-3

- Ideal:
  - Ideal channel state acquisition is assumed
  - No BF overhead is considered
  - 5G-LENA and mmWave modules for ns-3 have several ideal BF methods, e.g., beam search method, ideal DoA, long term covariation matrix based method, etc.
- Realistic:
  - Uses measurements to obtain the estimation of the channel state
  - BF overhead should be considered in this model
  - 5G-LENA did not support realistic type of BF methods (until the extension presented in this paper), mmWave module lacks such feature in the main development branch

The main contribution of this work, as the title says is ...

"Realistic Beamforming Design using SRS-based Channel Estimate for ns-3 5G-LENA Module"

Outline

The main parts of the presentation are:

- BF background
- An abstraction model to perform BF using SRS-based channel estimation
- Design and implementation of NR-standard compliant SRS for ns-3 5G-LENA module
- Design and implementation of realistic BF methods using SRS-based channel estimate in ns-3 5G-LENA module
- Simulation campaign to compare realistic vs ideal BF, and to highlight the importance of having realistic approach in the ns-3 5G-LENA module

Beamforming methods in real systems:

- *Direction of arrival (DoA) based BF*, i.e., estimates the DoA at the gNB from a UE transmitted signal, and vice versa, to determine the UE/gNB position and to steer the antenna array toward the receiver/transmitter.
- *Channel estimation based BF*, i.e., the gNB can directly estimate the channel from an uplink signal transmission from the UE, and use such a channel estimation for nearly optimal BF design. In 3GPP LTE and NR, the SRS have been specifically designed to be used for that purpose.
- *BF based on beam training and receiver's feedback*, i.e., the gNB has a set of pre-defined beams, over which it sends training signals, so that the UE can measure the received signal quality and then report the index of the best beam. Such procedures are standardized in both IEEE 802.11ad/ay and 3GPP NR.

Beamforming in NR TDD systems

- 3GPP NR has introduced Channel State Information Reference Signals (CSI RSs) and Synchronization Signal Blocks (SS blocks) for beam management in the DL and SRS for beam management in the UL.
- In TDD systems, due to channel reciprocity, SRS can be used for beam management in both DL and UL directions since:
  - Channel reciprocity enables the acquisition of the DL channel state information at the base station from an UL pilot-based transmission.
  - Also, beam reciprocity can be assumed (i.e., BF vectors for UL and DL are the same).

What is SRS?

- Sounding Reference Signal (SRS) is a reference signal sent in the UL (from UE to gNB) in 3GPP NR to measure the channel quality.
- SRS receptions at the gNB provide information about the combined effect of multipath fading and power loss of the transmitted signal from the UE.
- gNB can use SRS measurements for:
  - radio resource allocation and scheduling,
  - link adaptation (e.g., modulation and coding scheme selection),
  - inter-cell interference management, and
  - beam management.
- According to 3GPP NR specification (TS 38.211), SRS transmissions can be:
  - periodic
  - aperiodic
  - semi-persistent

SRS-based abstraction model

The estimation of the small-scale fading channel at the gNB can be modeled as:

$$\hat{h} = \alpha(h + e), \tag{1}$$

where:

- α is a scaling factor to maintain normalization of the estimated channel,
- h is the (complex-valued) small-scale fading channel between a UE and a gNB, and
- e is the white complex Gaussian channel estimation error, which is assumed to be characterized by zero-mean and variance σ_e^2 given by:

$$\sigma_e^2 = \frac{1}{(\mathrm{SINR} + \Delta)}, \tag{2}$$

  where
  - SINR is the received SINR of SRS at the gNB, and
  - Δ is the gain obtained from time-domain filtering during the channel estimation.

SRS-based abstraction model

The scaling factor is given by

$$\alpha = \sqrt{\frac{1}{(1+\sigma_e^2)}}. \tag{3}$$

Realistic BF algorithm using SRS-based abstraction model:

- Assuming independent small-scale fading among antenna elements, the model in (1) can be used to estimate each fading component of the 3GPP spatial channel matrix.
- Then, the channel matrix estimates can be used to select transmit/receive BF vectors.

Implementation features and assumptions

- In 5G NR, SRS parameters, such as periodicity and offset, can be:
  - configured by gNB and notified to UE through RRC messages, or
  - determined by gNB MAC scheduler and notified to UE through DCI format 2_3. This approach is:
    - flexible: the SRS parameters are adapted dynamically according to the actual number of UEs.
    - ns-3 users friendly: does not require to manually re-configure SRS periodicity each time that the number of UEs in the ns-3 simulation changes significantly (like in ns-3 LTE module).

We have implemented scheduling-based SRS.

Implementation assumptions - SRS in time/frequency domains

According to NR standard:

- In time domain:
  - SRS can be placed from 8th to 13th OFDM symbol in slot.
  - Can occupy **maximum 4 OFDM symbols in one slot**.
- In frequency domain:
  - The bandwidth for SRS can be adjusted and interleaving is permitted, i.e., multiple SRS signals (from different antenna ports or UEs) can be multiplexed in the same OFDM symbol. **A subset of subcarriers is being used**.

Implementation in 5G-LENA:

- In time domain:
  - **As per NS standard**, number of symbols configurable (1-4).
- In frequency domain:
  - Since the minimum transmission granularity in 5G-LENA module is a RB, **all subcarrierrs are used** for SRS transmission

ns-3 5G-LENA SRS example (time domain)

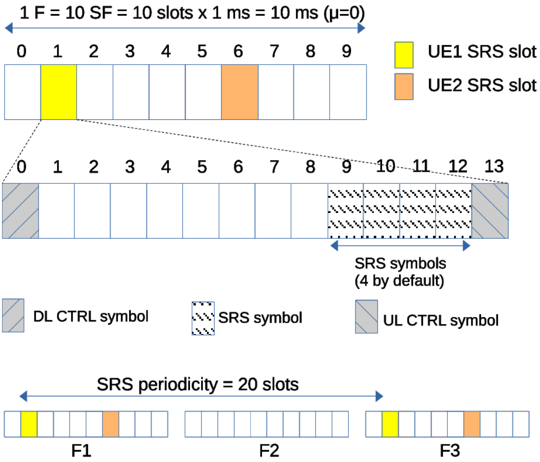


Figure: Example of SRS Transmissions of 2 Different UEs

New classes that allow dynamic SRS scheduling in 5G-LENA module

- `NrMacSchedulerSrs`:
  - An interface used by the NR gNB MAC scheduler to obtain the SRS offset/periodicity for a UE.
  - Different implementations of this interface that would simulate different algorithms for SRS offset/periodicity generation.
- One of possible implementations is provided in `NrMacSchedulerSrsDefault` which does the following:
  - Each time a new UE is attached it is called the function `AddUe` that returns the offset/periodicity configuration.
  - When scheduler detects that the SRS periodicity is too small for the number of UEs it calls function `IncreasePeriodicity`, which picks up the next periodicity value from the list of standard values, i.e., 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 160, 320, 640, 1280, 2560 slots.

ns-3 5G-LENA SRS configuration

`NrMacSchedulerNs3` class allows configuration of:

- The number of SRS symbols, 1-4 symbols, (through `SrsSymbols` attribute).
- Whether SRS will be transmitted in flexible slots (`EnableSrsInFSlots` attribute), and in uplink slots (`EnableSrsInUlSlots` attribute). Note that SRS can be completely disabled by setting both attributes to false.

5G-LENA BF extensions to provide support for realistic BF

- A new class is created, called `BeamformingAlgorithm`, which represents the main interface that any BF algorithm should implement, regardless it is ideal or realistic. The main function to be implemented in child classes is `GetBeamformingVectors` which determines the BF vectors to be used on a pair of devices, i.e., gNB and UE.
- Previously existing main BF class `IdealBeamformingAlgorithm` is changed to inherit the new `BeamformingAlgorithm` interface.
- Realistic BF algorithm based on abstraction model is implemented in `RealisticBeamformingAlgorithm` which uses SRS SINR measurements (also SRS SNR is added recently to 5G-LENA v1.2).

How it is implemented the realistic BF vector update?

- Realistic BF algorithm update considerations:
  - Trigger event: when the specific event occurs for the specific pair of devices (gNB and UE), i.e., we implemented the following events:
    - SRS count event: after N SRSs are received, the BF vectors are updated
    - Delay-based SRS update: δ time after SRS reception the BF vectors are updated
  - Trigger event type and parameters (N, δ):
    - can be configured through a new `RealisticBfManager` class
    - when using realistic BF it is necessary to install `RealisticBfManager` at gNBs PHY instead of the default `BeamManager` class
    - the configuration granularity is per gNB instance, but can be extended to be per UE
  - Device granularity: only the BF vectors of the pair of devices should be updated when the even occurs

  This is different from ideal BF algorithm implementations according to which the BF vectors of all the devices are updated at the same time based on the configured periodicity.

How realistic BF implementation works?

- First, when UE is attached to gNB, a BF task is created.
  - The BF task is composed of a pair of connected devices for which the realistic BF helper will manage the update of the BF vectors.
  - For each BF task is created an instance of realistic BF algorithm, which is connected to `NrSpectrumPhy` SRS SINR trace.
  - Each realistic BF algorithm instance is also connected to its helper through callback to notify it when BF vectors of device pair need to be updated.
- When BF vectors need to be updated, the function `GetBeamformingVector` of realistic BF algorithm is called, which calculates for each pair of pre-defined beams of the receiver and transmitter a channel estimate and based on that selects the best BF pair.

5G-LENA beamforming model extensions to support realistic BF

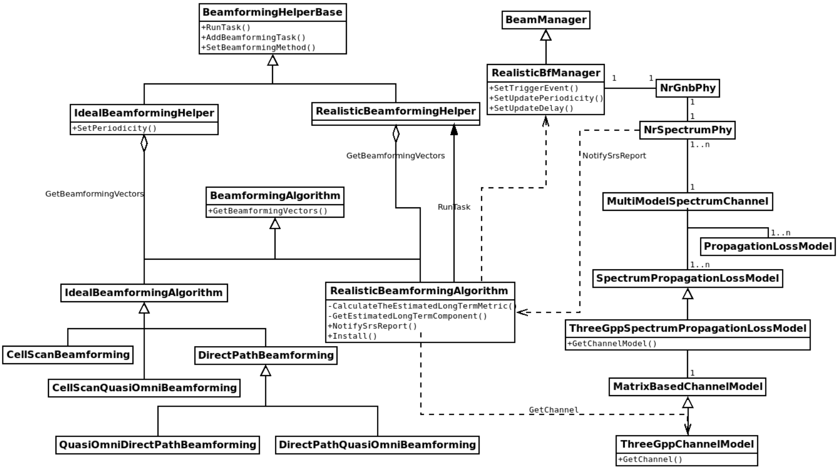
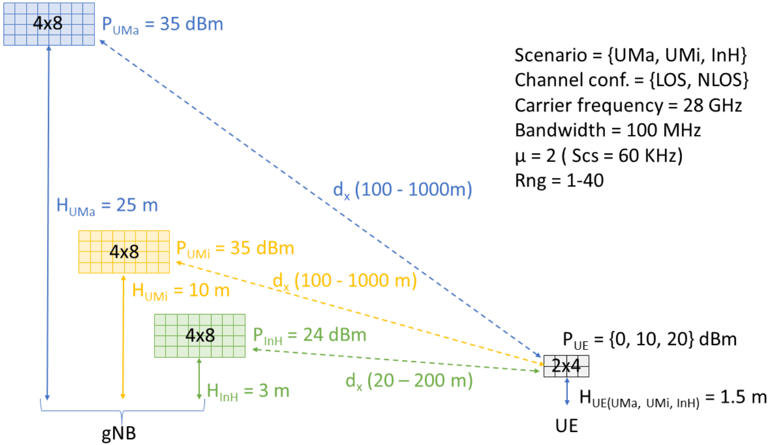


Figure: Diagram of Realistic/Ideal BF Model and Dependencies

Simulation scenario

- The topology consists of a single gNB and single UE, placed at a certain distance from each other and communicating over a wireless channel.
- Single MIMO layer is assumed.
- Duplexing: TDD
- The SRS is configured to use 1 OFDM symbol.

Simulation scenario - illustration and configuration parameters



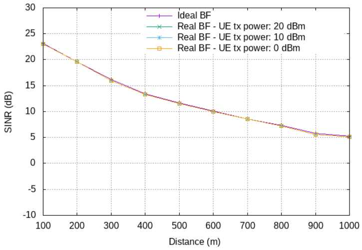
Scenario = {UMa, UMi, InH}
Channel conf. = {LOS, NLOS}
Carrier frequency = 28 GHz
Bandwidth = 100 MHz
μ = 2 (Scs = 60 KHz)
Rng = 1-40

Figure: Simulation scenario illustration

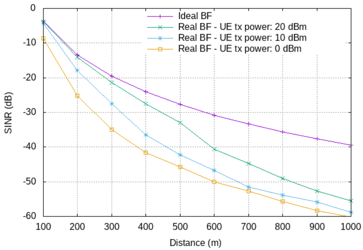
Simulation scenario (continuation)

- We compare ideal BF method using cell scan and the proposed realistic BF method (SRS-based).
- For each configuration of propagation scenario, LOS/NLOS condition, 3D distance and UE transmit power, we compute the average SINR received at the UE, in DL, to analyze the impact of the BF vector selection.
- The results have been averaged over 40 random channel realizations.

Results: Ideal vs Realistic BF



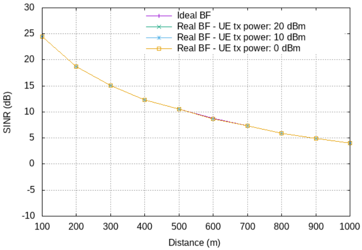
(a) UMa LOS



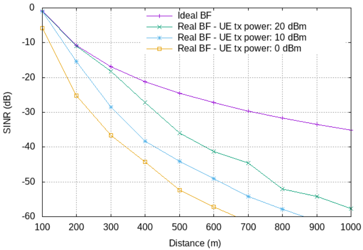
(b) UMa NLOS

Figure: Realistic vs Ideal BF in UMa Propagation Scenarios for LOS and NLOS condition

Results: Ideal vs Realistic BF



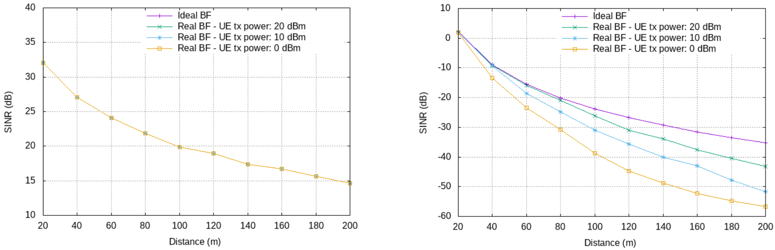
(a) UMi LOS



(b) UMi NLOS

Figure: Realistic vs Ideal BF in UMi Propagation Scenarios for LOS and NLOS condition

Results: Ideal vs Realistic BF



(a) Inh LOS

(b) Inh NLOS

Figure: Realistic vs Ideal BF in Inh Propagation Scenarios for LOS and NLOS condition

Conclusions

- We implemented an extension of 5G-LENA module to support simulations with realistic BF procedures in TDD systems. The key components are:
  - An abstraction model for the BF vector selection using SRS-based channel estimates
  - Dynamic SRS scheduling and SRS transmission and reception
  - General BF model to support the usage of both ideal or realistic algorithms and implementation of realistic BF algorithm
- The new models in 5G-LENA are easily extensible to support new algorithms for SRS scheduling and/or realistic BF.
- Since the realistic BF models more realistically real-world system behavior than the ideal BF (i.e., realistic BF is affected by poor channel condition), we consider it an essential feature for the ns-3 5G-LENA simulator.

Any questions?

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Source code: https://5g-lena.cttc.es/