Implementation of 2×2 MIMO in an LTE Module for the ns3 Simulator

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***Abstract*—Advanced communication techniques such as Multiple Input Multiple Output (MIMO) transmission are considered as possible extensions to the existing next generation cellular networks. However, their performance evaluation is either restricted to abstract analysis or limited to simplified scenarios with a small number of nodes. Instead, a comprehensive evaluation of these techniques in a network scenario is needed to capture the overall system performance. Inspired by this motivation, we present the implementation of a $2{\times}2$ MIMO transmission module in the well known ns3 simulator. We describe in full detail the classes involved and the related methods, and we present a performance evaluation campaign. We verify that the simulation results closely match the analysis, where available. At the same time, our simulation module offers the advantage of extending the analysis where this becomes impractical. Moreover, thanks to the modularity of the ns3 simulator, our code can be merged with any other evaluation at any point of the protocol stack, from the lower layers to the application.**

***Index Terms*—Cellular networks, LTE, MIMO systems, programming, modeling, network simulation.**

I. Introduction

DURING the last years, tremendous improvements of the transmission capabilities of wireless cellular systems were achieved. These enhancements relate to the development of efficient standards, which exploit advanced modulation schemes and channel-aware transmission scheduling to achieve high data rates. As a consequence, this has also led to an increased traffic demand by the users. For example, users of next generation networks, such as the Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) [1], will consider it normal to perform heavy traffic exchanges, e.g., involving multimedia communications, through the wireless channel. Thus, other efficient radio resource allocation techniques that may further improve the channel utilization are still sought.

Most of the candidate solutions propose advanced techniques at the physical (PHY) layer, other than smart user selection mechanisms and efficient modulation schemes. The main goal of PHY layer techniques is to control the interference mutually caused by wireless terminals, which is the most relevant obstacle to efficient and reliable communications.

In this paper, we focus on devices with multiple antennas which are able to realize a MIMO system. MIMO techniques have been analyzed in several contexts, but their application to a standard cellular network may be a problem due to the difficulty of fitting multiple antennas into a mobile phone with a slim form factor. However, we focus in this paper on a 2×2 MIMO system, i.e., with 2 transmit and 2 receive antennas, which, while keeping the analysis simpler, also offers a sufficient degree of realism.

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The main problem in the evaluation of MIMO systems is that, due to their mathematical complexity, their analytical assessment is often limited to simplified scenarios with a limited number of nodes. A way to address this problem may be to use simulation tools. Simulation platforms are used in the scientific community to test protocols and systems whenever the analytical tools are inadequate, because either the system is too complex or it cannot return a closed-form solution.

In this paper, we follow the approach of building an accurate representation of a 2×2 MIMO system and integrating it with a simulator of an LTE network. It is worth noting that, while simulators can overcome some burdens of the mathematical analysis, they also have complexity issues. However, we found that implementing a 2×2 MIMO system represents a good compromise solution that meets all the requirements of manageability and realism. Provided that the simulator is modular enough, such a solution can be conceptually easy to extend to larger antenna arrays.

We consider the ns3 network simulator [2], a well known open source tool that offers a modular and accurate representation of the whole protocol stack. We extend an existing LTE module of ns3, exploiting the post-processing Signal-to-Interference-plus-Noise Ratio (SINR) formulas for a MIMO system, which are investigated analytically in [3], [4].

The contributions of the present paper include the following elements. First of all, the simple Single-Input Single-Output (SISO) channel used by ns3 has been extended by considering realistic channel traces produced following the recommendations of the standard [5].

Moreover, the analytical approach presented in [4] was translated in the simulator's code so as to enable its usage. The resulting software is not affected by the mathematical complications that plague the analytical evaluations. While computational complexity may be still an issue (however, for a 2×2 system it is fairly manageable), the simulator does not need to derive any closed-form solution. On the other hand, while the analytical approaches necessarily have to consider an abstract version of the upper layers, the simulator with our added modules is able to give a comprehensive system view. Thus, the degree of realism of the results is highly improved.

Finally, we validated the resulting framework through two simulation campaigns to check the correctness of the implementation and also give quantitative insight on the performance of the implemented MIMO schemes. Such evaluations can be extended to a wide array of scenarios and represent a foundation for further contributions and investigations.

The rest of this paper is organized as follows. In Section II we review existing work on simulation frameworks for MIMO systems and discuss the references on which our implementation of MIMO is based. Section III gives instead the details of our proposed module, by describing all the classes that characterize it. In Section IV we present simulation results to validate our framework and compare the existing analytical results. Finally, we conclude in Section V.

II. Related Work

The importance of developing an accurate simulation platform for complex communication systems such as an LTE network is self-evident, given that several details of the LTE standard cannot be adequately captured analytically. We focus here only on those solutions that meet generality and reproducibility requirements for scientific purposes, and aim at modeling the entire system, not just certain parts of it.

In this spirit, there exist some system level simulators for LTE cellular systems that have been developed by equipment vendors, universities and research centers to realistically evaluate the performance of LTE. However, many of them do not make the source code publicly available. For example, a commercial physical layer simulation Toolbox implementation can be found in [6] or an LTE Specialized Model able to design LTE networks and devices is proposed in [7]. An open-source system level simulator developed in MATLAB is also presented in [8]; this work includes issues such as cell planning, scheduling and inter-cell interference but does not consider the upper layers of the protocol stack.

In this paper, we focus on extending an already available LTE module [9] of the open-source network simulator ns3 [2]. The code of the simulator is publicly available and several developers from the worldwide research community are free to contribute to it. The whole protocol stack is implemented; most of the modules involve the layers from datalink up, and this is true also for the models of LTE cellular networks. At the PHY layer, there is still room for many extensions, which should be produced in a modular fashion to be integrated with the rest of the existing implementations. Presently, the simulator is able to model a SISO channel with multiple user access. Within this framework, the developers can test resource allocation algorithms for a plain network with single-antenna terminals. Our contribution extends this framework to MIMO, and does so in a separable manner from the rest of the simulator.

We base our characterization of the MIMO system on existing analytical models and different practical implementations of the MIMO rationale [3], [4], [10]–[12]. The ns3 simulator operates by deriving SINR metrics and evaluating the resulting performance indicators from them. This may involve the estimation of the Channel Quality Indicator (CQI) according to the LTE standard, or the evaluation of theoretical capacity metrics, e.g., according to Shannon's theorem.

To keep the simulator approach modular, the overall idea is to exploit post-processing SINR formulas [3], so as to replace the plain evaluation of the ratio where interference is treated as noise with more advanced formulas, that depend on the applied policy for interference management. Similar formulas are used, e.g., to select an optimal subset of transmit antennas in a spatial multiplexing system in [13].

Our implementation includes several MIMO transmission schemes. LTE supports rank-1 transmit diversity and multi-rank transmission to select the optimal MIMO scheme that suits the channel conditions of the mobile. In rank-1 transmit diversity, the Alamouti space-time block code [10] is used, which improves the SINR at the receiver's side in case of high interference or weak signal. In multi-rank transmission multiplexing [11], [12] multiple information streams are sent to the receiver to increase throughput, but this solution is appropriate in high SINR regions with rich scattering environments.

III. Implementation

Our developed module implements two different MIMO transmission modes: Trasmission Diversity and Open Loop Spatial Multiplexing. The former has been implemented by closely following Alamouti's precoding scheme [10], while the latter makes use of several models proposed in [4] based on different receiver designs: zero forcing (ZF) [14], minimum mean-squared error (MMSE) and ordered successive interference cancellation based on MMSE (OSIC-MMSE) [15].

Although we modeled two transmit and two receive antennas, the traces used for the channel can be modified for other channel models or configurations and the SINR expressions can be extended to systems with a different number of antennas, precoding schemes or receiver implementations. The module creates three new classes that are inserted within the LTE module of ns3, *MimoRxSignal*, *ScmMimoChannel* and *TransmissionMode*, described in the following subsections.

A. *MimoRxSignal*

SISO systems require the knowledge of a single channel coefficient. For MIMO systems we need a matrix $\mathbf{H}$, modeling the channels between all possible antenna pairs. The elements of $\mathbf{H}$ are complex coefficients h_{ij} representing the instantaneous gain due to fast fading from transmit antenna j to receive antenna i.

Class *MimoRxSignal* manages these parameters. It provides a flexible structure that includes a *MimoRx* object for every combination of a transmit and a receive antenna. *MimoRx* objects consist of four *SpectrumValue* [2] instances describing the power spectral density of the signal, the real part of the coefficient h_{ij}, the imaginary part of the coefficient h_{ij}, and the magnitude of the coefficient h_{ij}, respectively, in the domain of the whole LTE bandwidth. All the instances are populated by the class *ScmMimoChannel*.

B. *ScmMimoChannel*

For the channel model, we used several traces representing the complex coefficients h_{ij} for every LTE subframe, based on 3GPP SCM model [5]. The traces are generated offline by a two-step process. In the first step, a MATLAB script available at [16] is used to generate the time-domain coefficients $\eta_{ij}[n]$ with n as a time index. In the second step, we obtain the

TABLE I: Channel parameters

Number of antennas at the transmitter	2
Number of antennas at the receiver	2
Distance between elements at transmitter in wavelenghts	6
Distance between elements at receiver in wavelenghts	0.4
Transmitter per path Angle Spread in degrees	2
Receiver per path Angle Spread in degrees	35
Number of paths — subpaths	6 — 20
Path power in dB	[-3,...,-16]
Path delays in μs	[10,...,60]
Receiver velocity in km/h	2

equivalent frequency-domain channel coefficients for every LTE resource block by Fast Fourier Transform. The downlink of LTE uses an Orthogonal Frequency Division Multiple Access (OFDMA) scheme, where the allocation atom is a Resource Block (RB), which consists of a unit element in both time and frequency.

Thus, for every RB r we get a matrix of coefficients

$$\mathbf{H}[r] = \begin{pmatrix} h_{11}[r] & h_{12}[r] & \dots & h_{1S}[r] \\ h_{21}[r] & h_{22}[r] & \dots & h_{2S}[r] \\ \dots & \dots & \dots & \dots \\ h_{U1}[r] & h_{U2}[r] & \dots & h_{US}[r] \end{pmatrix} \quad (1)$$

where S is the number of transmit antennas, U the number of receive antennas and $r = 1, ..., N_{RB}$, with N_{RB} being the number of resource blocks. The coefficients $h_{us}[r]$ are derived through FFT from the multipath components $\eta_{ij}[n]$, so that the variability of the gains throughout the subchannels depends on the shape of the frequency response of the channel, while over time it depends on the correlation of the $\eta_{ij}[n]$'s. Such a structure provides a realistic generalization to a $U \times S$ matrix of a SISO channel with just one coefficient.

The channel parameters used to generate the trace inserted currently in the module are given in Table I, while Fig. 1 shows the fast fading gain graphs obtained for two different antenna pairs in the resource-block/time domain.

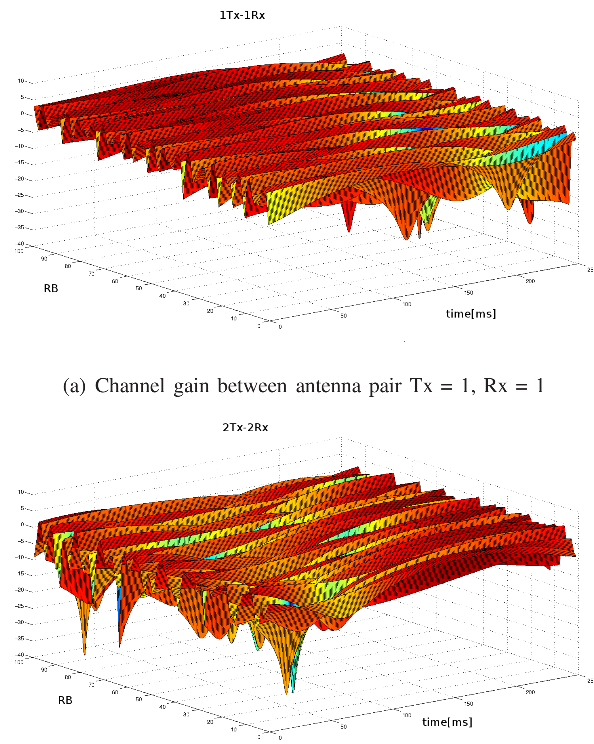
C. *TransmissionMode*

The class *TransmissionMode* computes the post-processing SINR for the different MIMO systems implemented. The SINR formulas are based on [4] for a 2×2 MIMO system, with slight modifications for interference terms. for which we consider the possibility of multiple transmitters. Thus, we denote with h_{ijk} the term h_{ij} related to the kth transmitter. Also, the RB index r is omitted for notational simplicity, as the procedures are simply repeated for every RB.

For the **transmission diversity** case, which corresponds to transmission mode 2 of the downlink of the LTE standard [5], we considered the Alamouti scheme [10]. The SINR for the zth receiver, under the assumption that noise plus co-channel interference can be treated as complex Gaussian [17], is

$$SINR_z = \frac{\sum_{i=1}^{N_{rx}} \sum_{j=1}^{N_{tx}} P_{zjk} \mid h_{ijk} \mid^2}{\sigma^2 + \sum_{m \neq k} \sum_{i=1}^{N_{rx}} \sum_{j=1}^{N_{tx}} P_{zjm} \mid h_{ijm} \mid^2} \quad (2)$$

where N_{rx} is the number of antennas at the receiver, N_{tx} is the number of transmit antennas, k is the index of the



(a) Channel gain between antenna pair Tx = 1, Rx = 1

(b) Channel gain between antenna pair Tx = 2, Rx = 2

Fig. 1: Fast fading gain matrix for different antenna pairs

intended transmitter, $P_{zj\ell}$ is the power received at receiver z from the jth antenna of transmitter ℓ after path and shadow fading losses, and σ^2 is a noise term. Note that the SINR formula refers to the whole receiver z.

Conversely, in **spatial multiplexing** we need to know the SINR value for every antenna at the receiver's side. For the ZF receiver the SINR post-processing expression for the ith antenna of receiver z is derived as [13]

$$SINR_{z,i} = \frac{P_{zik}}{\sigma^2 \left[H_k^* H_k\right]_{ii}^{-1} + \sum_{m \neq k} \sum_{j=1}^{N_{tx}} P_{zjm} |h_{ijm}|^2 [H_k^* H_k]_{ii}^{-1}} \quad (3)$$

where $N_{rx} \times N_{tx}$ matrix $\mathbf{H}_k$ refers to the intended transmitter.

In the case of an **MMSE receiver**, the SINR is [4]

$$SINR_{z,i} = \underline{h_{ik}^*} R_{ik}^{-1} \underline{h_{ik}}, \quad \text{where:}$$

$$R_{ik} = \underline{h_{\ell k}} \underline{h_{\ell k}^*} + \frac{\sigma^2 + \sum_{m \neq k} \sum_{j=1}^{N_{tx}} P_{zjm} |h_{ijm}|^2}{P_{zik}} \mathbf{I}_2, \; i \neq \ell \quad (4)$$

where ℓ is the other antenna than i, $\mathbf{I}_2$ the 2×2 identity matrix, $\underline{h_{ik}}$ the ith column of $\mathbf{H}_k$, and $*$ denotes conjugate transpose.

The **OSIC-MMSE** case is an improvement of MMSE, where ordered successive interference cancellation is performed [15]. The related SINR post processing expression is obtained differently for the two antennas; first, SINR MMSE post-processing is applied for both antennas, and then the substream with the highest SINR is detected and cancelled.

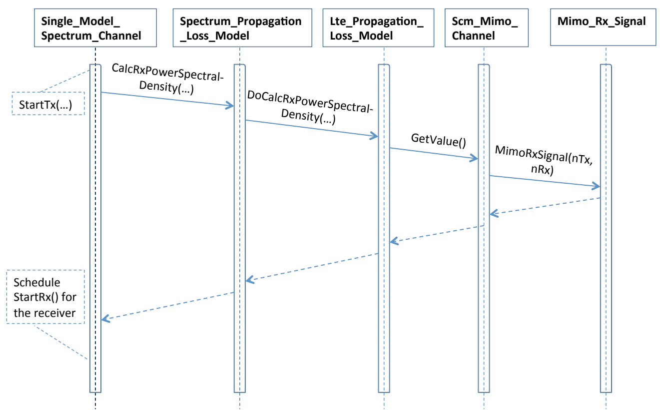


Fig. 2: StartTx method for the transmitter

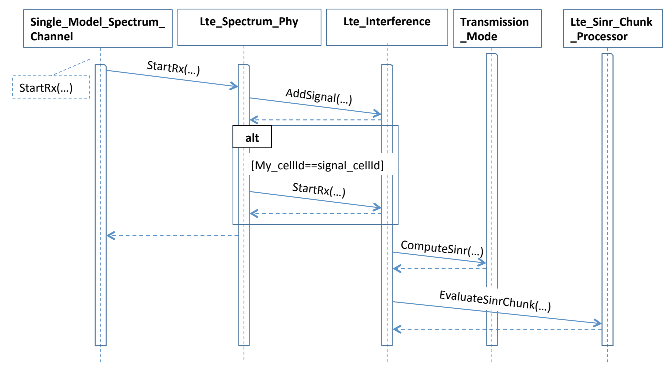


Fig. 3: StartRx method for the receiver

If we denote it with i then its SINR is still according to (4). Instead the SINR of the other substream, labeled ℓ, is

$$SINR_{z,\ell} = \frac{\underline{h}^*_{jk}\underline{h}_{jk}P_{z\ell k}}{\sigma^2 + \sum_{m\neq k}\sum_{j=1}^{N_{tx}} P_{zjm}|h_{\ell jm}|^2}. \tag{5}$$

In all the MIMO schemes described above, perfect knowledge of the channel at the receiver is assumed.

The UML sequence diagrams reported in Figs. 2 and 3 describe the interactions between the new classes and the existing LTE modules of ns3. Fig. 2 represents the transmission of a signal, and shows that the new classes *ScmMimoChannel* and *MimoRxSignal* are connected to the class *SingleModelSpectrumChannel* belonging to the Spectrum Framework of ns3 through the methods of the *SpectrumPropagationLossModel* class and the *LtePropagationLossModel* class [9]. Fig. 3 shows instead the receiver's operation. The class *LteSpectrumPhy* separates the useful signal from interference to compute the SINR from the *LteInterference* class. Within the instance transmission mode the programmer can set, directly from the simulation script, a variable *t-mode* in order to redirect the method *ComputeSinr(..)* into the MIMO scheme of choice.

In terms of computation complexity, using MIMO schemes with the proposed approach increases the load by a factor of $N_{rx} \times N_{tx}$. Interestingly, the new classes proposed can be applied with relatively minor modifications to any other air-interfaces using OFDMA for multiple access [18].

IV. Simulation Results

We ran two simulation campaigns using the approach implemented in ns3 that computes the Transport Block size considering the modulation and coding as per the standard specification [1].

In the former, we compare the simulation results with the approaches proposed in the literature to test the accuracy of our implementation. The analytical results may have limited validity in practical cases, as they necessarily neglect certain implementation aspects of the LTE standard (e.g., that the data rate is upper bounded by the highest order modulation scheme). Our simulation framework closely matches the analytical results where they are meaningful, while it generalizes them when they are no longer consistent with the system at hand (e.g., in high SINR regions).

In the latter campaign, we compare different MIMO schemes in terms of their spectral efficiency in the downlink. The purpose is to show that, even though some schemes cannot be evaluated through exact mathematical formulas, the simulator is still able to offer a quantitative comparison.

TABLE II: Simulation parameters

Center frequency	2.1 GHz
Channel Bandwidth	5 MHz
Subcarrier Bandwidth	15 kHz
$RB_{bandwidth}$	180 kHz
$RB_{subcarriers}$	12
Noise figure	5 dB
Noise Spectral Density	-174 dBm/Hz
Path loss model	COST Hata model (suburban areas)
BS antenna height	32 m
MS antenna height	1.5 m
Frame duration	10 ms
TTI	1 ms
Simulated interval	25 s

The main system parameters used in the numerical evaluations are reported in Table II. Both campaigns consider a single cell scenario, therefore intercell interference is absent and the SINR simply becomes SNR (Signal-to-Noise Ratio). This choice is not due to a limitation of the simulator, but rather to make a meaningful comparison with the analysis. We remark that the extension to multiple cells would be straightforward in the simulator (but not in the analytical framework).

Fig. 4 shows the results obtained by the first simulation. The theoretical curves are given by the formula provided in [3], whose parameters have been also fitted to our scenario and the LTE standard. The value of the SNR is given by the ratio between the power at the receiver after macro and shadow fading losses and the noise value. Note that the channel model is slightly different from that considered in [3]; in spite of that, simulated and theoretical curves are similar below 35 dB, after which we obtain a saturation of the simulated curves. As argued above, this effect is due to the LTE system reaching the highest modulation and coding scheme it can be assigned depending on the SNR. Moreover, Fig. 4 shows that the performance of the ZF system is better than that of the SISO system for high SNR, and this behavior matches what expected from the theoretical analysis.

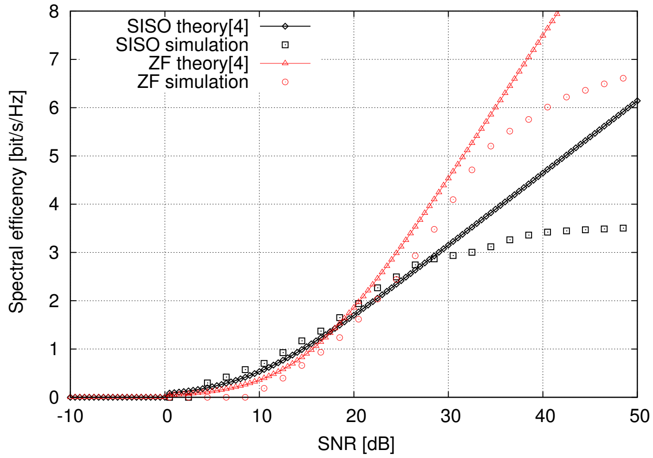


Fig. 4: Theoretical versus simulated spectral efficiency

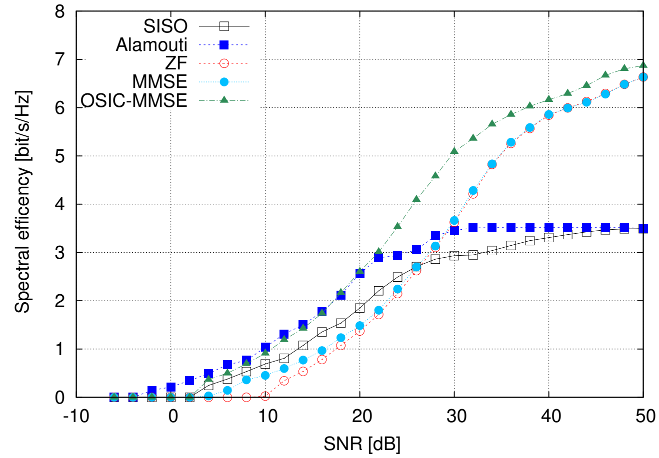


Fig. 5: Comparison among the implemented MIMO schemes

The theoretical approach used in [3] provides the performance analysis only in the cases of SISO and ZF systems. However, thanks to our module we can extend the same analysis to the transmit diversity case and to other spatial multiplexing cases. Our second simulation campaign, whose results are reported in Fig. 5, investigates the performance of the different MIMO schemes implemented in the module in terms of spectral efficiency. As in Fig. 4, the SNR considered is the ratio between the power at the receiver after macro and shadow fading losses and the noise value. An analysis of the curves related to the MIMO spatial multiplexing schemes (ZF, MMSE, OSIC-MMSE) highlights that the OSIC-MMSE receiver, thanks to the iterative signal detection, achieves the best performance. Comparing the MIMO-MMSE curve with the MIMO-ZF curve, we notice that the MIMO-MMSE receiver provides better performance than MIMO-ZF below an SNR of 20 dB. This behavior is due to the improvement given by MMSE over ZF to reduce the impact of noise, and it is more pronounced in the region of low SNR.

Alamouti MIMO is the only diversity-based scheme included in our framework. This kind of system aims at improving the post-processing SNR at the receiver. In Fig. 5, we see how the Alamouti system achieves the best performance in the low SNR region. This result confirms that spatial multiplexing MIMO solutions are optimal only for high SNR (or SINR).

V. Conclusions and Future Work

We described the implementation of a 2×2 MIMO system in the simulation of LTE networks, within the well known network simulator ns3. Several MIMO techniques were framed into our approach, and the results were compared and discussed. Simulation campaigns verified the proposed framework, whose results match and extend the analysis.

Therefore, our proposed module can serve as a concrete tool to evaluate the performance of MIMO systems in LTE networks [19]. Due to the inherent complexity of framing MIMO schemes in a comprehensive system view, the proposed approach appears as a very good candidate for researchers and practitioners to gain understanding on this kind of technology.

We plan to extend the module with beamforming techniques and implement Multiuser MIMO. We also intend to study cellular networks with high intercell interference, simulating scenarios with high user density.

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