Simulation Framework for MIMO LTE Network Performance Analysis

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Abstract. The paper presents a cloud-based virtual server environment for simulations of MIMO LTE networks at Telecommunications Research Center, Vilnius University. Brief information about analytical models for simulating the performance of mobile wireless network is given including antenna analysis, radio propagation channel and radio interference estimation problems. Architecture of software framework is discussed, illustrated by LTE network simulation scenario.

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Introduction

Widely spread nature of today's telecommunication networks provides not only extensive possibilities and many advances in various fields of human life, but also requires constant development of new technologies to support growing demand for communications capacity. Telecommunications Research Center has been founded at Faculty of Physics, Vilnius University in collaboration with telecommunication industry companies *Huawei technologies Co.* Ltd., *Omnitel* Ltd. and *Blue Bridge* Ltd. to provide an experimental testbed for research and adoption of new telecommunication technologies.

Complexity of wireless network research problems requires close comparison of experimental measurements with numerical simulations. Measurements conducted in isolated in-lab base station can be extrapolated to network-wide multicellular environment. High accuracy of numerical results can be achieved using long running statistical Monte Carlo simulations. For this purpose a cloud-based virtual server environment has been developed allowing to run massive simulations and interactively share results between team members.

The most important questions under the study at Telecommunication Research Center are related to 4G LTE (Long Term Evolution) mobile wireless networks that are currently entering the commercial market [1]. Introduction of new network technologies always depends on many technological and economical factors such as limited frequency resource availability, the cost and operational conditions of sophisticated radio equipment and thorough network planning and optimization process. Efficient analytical techniques are required for planning and analysing the wireless networks.

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1. Analysis Methods

In order to build reliable analytical models reflecting operation of real mobile networks, multiple effects should be taken into account as presented below.

1. Transmitting and receiving antenna characteristics (radiation patterns and frequency response). In multiple-input multiple-output (MIMO) antenna configurations, mutual coupling between individual antenna elements becomes a limiting factor on the large scale MIMO applications and should be taken into account [2].
2. Correlation between MIMO antennas sets the limits for maximum data throughput available for a given transmitting and receiving antenna configuration. For the correlation analysis, antennas should be modeled not as isolated entities, but in relation to the radio propagation channel effects such as multipath reflections and scattering. The most important radio channel realizations for 4G applications have been collected by European initiated WINNER, WINNER II and WINNER+ projects to define 3GPP related MIMO channel properties - see Refs. [3-5]. Statistically processed results of these measurement campaigns have been used for numerical simulations of radio propagation effects.
3. Radio interference analysis is another important factor in modern capacity-limited networks operating in dense multi-cell configurations [6-7]. Two basic types of interference are considered in this paper, namely, intra-system interference between neighboring LTE cells and external interference arising from other radio communication systems, deployed in adjacent frequency bands.

As an example, the impact of pulsed radar signal interference on LTE network performance is discussed here.

To fully describe the effects of propagation and interference on wireless system performance, detailed simulations of radio modulation, multi-user scheduling and multiple access scheme should be included into analysis.

The following subsections provide short overview of mathematical models used in LTE network simulations.

1.1. MIMO Channel Capacity

MIMO antenna systems were introduced with 4G wireless communications and remain promising candidates for upcoming 5G radio technologies [8]. The main goal of MIMO antennas is to increase data transmission throughput via the same radio channel bandwidth while at the same time ensuring high quality of service to multiple mobile users. Achieving high MIMO performance requires knowledge of statistical properties of radio propagation channel and optimization of transmitter-receiver antennas. By using numerical methods antenna radiation patterns can be adjusted according to the spatial distribution of mobile users.

For MIMO channel model, described by matrix-type equation [9]

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{y}$ and $\mathbf{x}$ are columns of sizes N_r and N_t, respectively, $\mathbf{H}$ is $N_r \times N_t$ matrix with N_r and N_t denoting the number of receive and transmit antennas. The noise can be expressed as

$$\mathbf{n} = \sigma_n^2 \mathbf{I}_{N_r} \tag{2}$$

where σ_n^2 is the variance of additive white Gaussian noise (AWGN) and $\mathbf{I}_{N_r}$ is an identity matrix of the size N_r. The average signal-to-noise ratio SNR

$$SNR = \frac{P_0}{\sigma_n^2} = \frac{E\left[\mathbf{x}^2\right]}{\sigma_n^2} \tag{3}$$

where $P_0 = E\left[\mathbf{x}^2\right]$ is an average received signal power.

Shannon capacity for MIMO channels is defined by multiplexing gain - the number R of independent parallel channels. MIMO channel capacity using modified Shannon's mutual information C of all input covariant matrices $\mathbf{R_x}$:

$$\mathbf{R_x} = E\left[\mathbf{x}\mathbf{x}^H\right], \tag{4}$$

is expressed as

$$C = BW \cdot \log_2 \det\left[\mathbf{I}_{N_r} + \mathbf{H}\mathbf{R_x}\mathbf{H}^H\right], \tag{5}$$

where BW is the system bandwidth.

For equal power allocation to all transmit antennas,

$$\mathbf{R_x} = \frac{P_0}{N_t}\mathbf{I}_{N_t} \tag{6}$$

and capacity expression becomes

$$C = BW \cdot \log_2 \det\left[\mathbf{I}_{N_r} + \frac{SNR}{N_t}\mathbf{H}\mathbf{H}^H\right]. \tag{7}$$

Using singular value decomposition, channel transfer matrix $\mathbf{H}$ can be diagonalized as

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^H, \tag{8}$$

where

$$\mathbf{D} = \mathrm{diag}\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, ..., \sqrt{\lambda_m}, 0, 0\right) \tag{9}$$

and $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices. Continuing similar analysis to MIMO channels with available channel state information (CSI) at the transmitter, capacity optimization can be achieved using transmit pre-coding techniques [9-10].

1.2. LTE Related Interference Estimation

Among our recent research topics there is the investigation of interference to which new LTE technology will be subjected, such as TV and radar signals operating in the neighboring frequency bands. To estimate proper conditions under which new technology would coexist with established wireless systems is of uttermost importance before beginning implementation of a new network infrastructure.

Most of the previous studies of interference effects on MIMO system capacity takes into account co-channel intra-system interference with AWGN [11-12]. We consider interference to LTE downlink transmission consisting of inter-cell and external radar interference. Each sub-carrier k per victim symbol will be interfered by radar differently according to the pulse spectrum, giving rise to a number of signal-to-interference-plus-noise ratios (SINR) $\gamma_{m,k}$ of the received signal at the terminal unit m in downlink estimated per each sub-carrier k, $k = 1, ..., K$, where K is the total number of sub-carriers:

$$\gamma_{m,k} = \frac{P_{s,k}g_{s,m}}{I_{IC} + I_R + \sigma_n^2}, \tag{10}$$

where $P_{s,k}$ is transmit output power of the serving base station (eNodeB) s per sub-carrier k, $g_{s,m}$ is radio channel gain including antenna gains and path losses between base station s and mobile user m, I_{IC} is the inter-cell interference, I_R is the external radar interference and σ_n^2 is the variance of AWGN.

The inter-cell interference I_{IC} depends on the traffic loading ρ_j in neighboring cells, and the loading itself is a function of local SINR value in neighboring cells therefore posing optimization problem. Radar interference term I_R depends on the spectrum overlap between LTE and radar signals and can be estimated from known signal waveforms [13].

A new feature in 4G voice communications is VoLTE (Voice over LTE) representing an evolutionary step over VoIP (Voice over IP) [14]. Recently, we have been performing tests for network capacity and voice transmission quality using

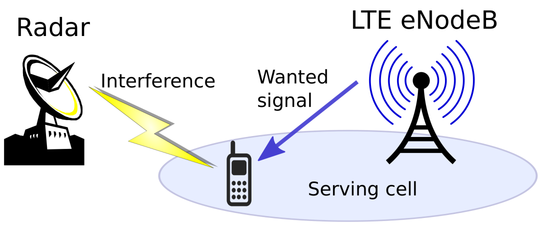

Fig. 1. Radar to LTE interference geometry.

VoIP technology subjected to various interference effects. Having in mind high data rates and many impairments in the real world transmission channels, such experiments require many well-tuned measurements, especially focusing on time synchronization between remote network nodes.

The performed experimental measurements of pulsed radar signal impact on live LTE base station have been compared with numerical simulations, which enabled us to estimate allowable radar signal power levels. Interference geometry is depicted in Fig. 1 representing the mobile receiver connected to the serving base station (eNodeB) and subjected to external interference from the nearby located radar. Fig. 2 represents experimental measurements (PESQ) and theoretical predictions.

The results represent measured VoLTE PESQ (Perceptual Evaluation of Speech Quality) and simulated number of possible voice calls which reduces to zero when radar signal power increases - see Fig. 2. The zero points of calls number represent the thresholds of radar power levels which totally block VoLTE service.

2. Simulation Framework

A more detailed description of simulation algorithms is available in our recent publications [13,15]. They are based on statistical Monte Carlo simulations implemented using GNU Octave [16] and Python numerical libraries [17].

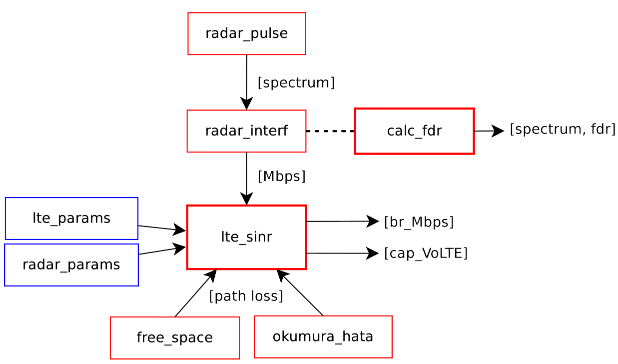

Fig. 3. Numerical simulation functions for VoLTE and radar interference analysis.

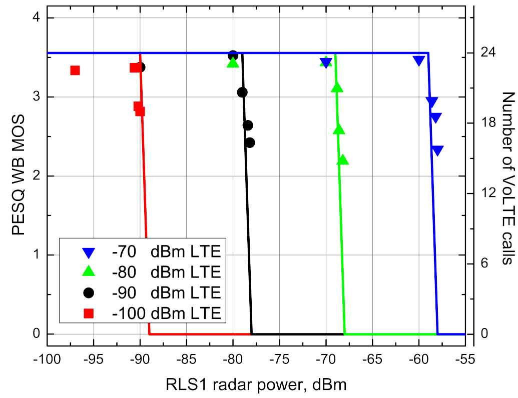

Fig. 2. Experimental measurements (PESQ) and theoretical predictions of maximum number of VoLTE voice calls.

The simulation scenario consists of processes randomly generating mobile users over network's cell area, simulating radio propagation channel, estimating path losses and multipath fading effects on received signal from the serving base station. In addition, neighboring base stations with their own mobile user distributions are generated which impose intercell interference.

The results are statistically averaged over multiple snapshots of randomly generated mobile user locations within each network cell.

A schematic diagram of software packages used for assessment of external interference from nearby radar transmitter into LTE downlink service is shown in Fig. 3. It includes functions for pulsed radar signal generation (`radar_pulse`), a module for radar interference estimation (`radar_interf`) with suplementary function `calc_fdr`, which can output graphical results of spectrum overlap between radar and LTE signals.

The main module for simulations `lte_sinr` accepts user defined LTE (`lte_params`) and radar (`radar_params`) configuration parameters and allows to select path loss model (`free_space` or `okumura_hata`). `lte_sinr` module is used to run Monte Carlo simulations over multiple mobile user distributions and output results in the form of Mbps for data rate or maximum number of voice calls for VoLTE service.

High-throughput computing software package HTCondor developed at University of Wisconsin-Madison [18] is used for scheduling long running computing jobs and to provide task parallelization on multi-core processors. HTCondor supports message passing interface (MPI) applications, implemented using GNU Octave or Python numerical libraries.

The output of simulations is generated in the form of tables and graphics which have to be compared against measurement results. The algorithm development and experimental measurements in our lab have been performed by different

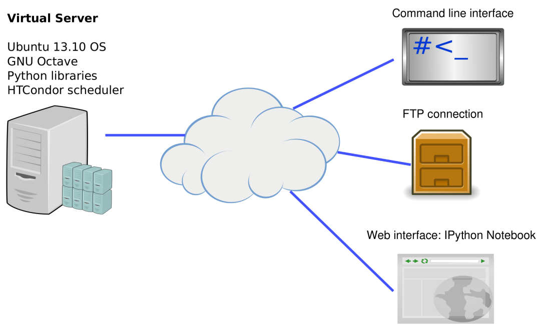

Fig. 4. Virtual server environment.

team members, therefore effective and timely sharing of the simulation results has been of high importance. We required the ability for experimenters to modify simulation parameters for adapting to real measurement conditions, repeat the simulations and obtain dynamical prediction results in tabular format suitable for further data processing.

Additionally, the requirement of remote access preferably via standard web browser was essential in order to be able to launch calculations and check the progress of long running simulations remotely.

To meet these requirements we built a cloud-based virtual server environment on Linux Ubuntu 13.10 OS, loaded with GNU compilers and numerical libraries (Fig. 4.). For MIMO LTE simulations we used algorithms implemented in GNU Octave and Python scripts. Several software interfaces were made available for users with three different roles.

1. *Command line interface* via secure shell (SSH) connection is used for algorithm development and testing, system installation and configuration.
2. Secure *FTP connection* over SSH is available for data exchange between local and remote computers to upload large input datasets and download raw simulation results for further post-processing and visualization.
3. *IPython Notebook* [19] server has been implemented in order to have the ability to run simulations online without the knowledge of Linux shell programming. It allows experimenters to connect to the virtual server via standard web browser (using HTTPS authentication) to modify simulation parameters, run calculations and preview simulation results.

Implemented interfaces allow sharing the same algorithm code base between a group of researchers without the need of reinstallation of software libraries on user computer.

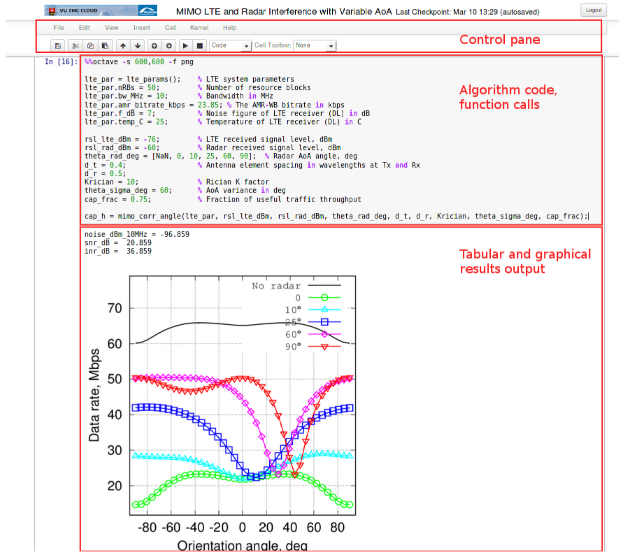

Fig. 5. Web view of IPython Notebook user interface.

Web view of one of LTE simulation results is shown in Fig. 5. It provides the area for entering and modifying algorithms, launching calculations and previewing simulation results.

Conclusions

Easy to use and maintain virtual server environment has been implemented for MIMO LTE communication system modeling.

The framework allows to perform long running Monte Carlo simulations involving multiple modules of physical network layer. Simulation algorithms can be shared by experimenters which are able to modify input parameters and run live simulations corresponding to real measurement conditions.

The implemented framework reduces technical work required for exchanging results between members of research team and minimizes maintenance procedures of the virtual server system.

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