Overview of the MACHINE - a set of software simulation tools for mobile networks evaluation

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Abstract—MACHINE stands for Mobile networks evaluation tools with Advanced CHannel and INterference modEling. In this paper we present a set of software simulation tools entitled MACHINE and intended for performance evaluation of mobile wireless networks and radio access technologies. These tools were developed at Poznań University of Technology in the Chair of Wireless Communications and are extensively used in the study of 4G and 5G wireless systems.

Index Terms— D2D, link level simulations, link to system interface, LTE, MACHINE, MIMO, relaying, system level simulations, two way relaying

I. INTRODUCTION

SIMULATION is a powerful tool that can be used in evaluation of wireless networks and radio access technologies. Indeed extensive simulations were performed by various parties in the evaluation of 2G, 3G, and 4G standards prior to their field tests. The level of details and scale of modeled networks in these evaluations were increasing from generation to generation of wireless cellular networks. It is common to define complex models in a very detailed way to enable comparison of results obtained by different researchers or companies.

In this paper we present a set of software simulation tools entitled MACHINE and intended for performance evaluation of mobile wireless networks and radio access technologies. These tools were developed at Poznań University of Technology in the Chair of Wireless Communications and are extensively used in the study of 4G and 5G wireless systems. In section two we start with general overview of the simulation tools and in the subsequent sections we present in a more detailed way some of them. We conclude with discussion of current development plans for the MACHINE.

II. MACHINE

Basic structure of the MACHINE is shown in Fig. 1. It consists of two major parts: the simulated system model (SSM) and radio environment model (REM). The REM is an abstraction of the wireless networks and radio waves propagation effects. Currently there are two major models implemented. The first one is based on the IMT-Advanced evaluation framework [1] and models cellular networks mostly as hexagonal grids (there is one scenario that consists of a single floor in a building). This tool was implemented during work of the first author in the WINNER+ project. The second REM, called MGM, is based on the METIS project’s test case (TC2) scenario [4, 18] and models a 3D map based city structures. Both of these tools use the same tool for modeling small scale fading effects - the SSE-MACHINE. The SSM module of the MACHINE consists of three major parts. The first one is a link level simulator (LLS-MACHINE) that is based on the physical layer of the LTE system [12]. It implements both uplink and downlink data and control channels. LLS-MACHINE is able to simulate multiple links. The abstraction model of the LTE link facilitates the second major part of SSM - the link to system interface (L2S-MACHINE). The L2S interface is utilized by the system level simulator (SLS-MACHINE) which is the third major part of SSM. The SLS models LTE-like cellular networks operating in IMT-Advanced or METIS TC2-like scenarios.

From the programming point of view the core processing in MACHINE is written in C++ with the help of IT++ library [13]. Post processing of the obtained results is implemented mainly in Python with the help of matplotlib [15] and numpy [16] libraries. The tools can be developed and executed at least on the MS Windows and Linux platforms. Typically the simulation results are obtained by running in parallel multiple simulations on the Chair of Wireless Communication’s computation cluster capable of running simultaneously several hundred tasks (each on a separate processor core).

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III. IMT-ADVANCED EVALUATION FRAMEWORK

The IMT-Advanced evaluation framework was specified in [1] for evaluation of 4G technology proposals [4,8,9,10]. This framework specifies a set of scenarios in which 4G compliant technologies should operate fulfilling defined performance indicators. The proposals should be evaluated through simulation, as well as through analytical and inspection procedures. The simulations are defined by providing network layout, deployment, and channel model specification for each scenario. There are four mandatory scenarios: indoor hotspot (InH), urban microcell (UMi), urban macrocell (UMa), and rural macrocell (RMa). The InH scenario assumes deployment of two base stations in a single floor of an office building. The remaining scenarios assume a hexagonal grid of base stations with different inter site distances and maximum allowable transmit powers. In each scenario users are deployed randomly following uniform distribution. For each scenario a set of parameters is specified for the generic IMT-Advanced channel model. The ITU-R IMT-Advanced channel model is a geometry-based stochastic model and is often called a double-directional channel model. In such a model, directions of the rays departing from the transmit antennas and arriving at the receive antennas are specified without the precise location of the scatterers. Thanks to this approach, propagation parameters and antenna parameters can be separated.

The coefficients of each channel are generated in a stepwise procedure. First, the propagation scenario is selected, and the environment parameters for this scenario are defined. After that, the network layout is set up by generating base station positions according to the network topology and by randomly generating the positions of the user terminals and directions of their motion. For a given scenario, the speed of all user terminals is fixed. In the next step, large-scale parameters are generated. First, line-of-sight (LOS) or non-line-of-sight (NLOS) propagation conditions are set. After setting the LOS/NLOS conditions, the appropriate path loss formula is applied for each link. Subsequently, large-scale parameters are generated for each link. These are delay spread (DS), angle spread of arrival (ASA), angle spread of departure (ASD), Ricean K factor (K), and shadow fading (SF). After large-scale parameters are fixed for each link, the generation of small-scale parameters takes place. For each propagation scenario, the number of clusters is given in [1]. First, cluster delays in a given link are generated based on the DS parameter. After that, cluster powers are generated using a particular cluster delay as a parameter. The last step in the small-scale parameters generation is the calculation of departure and arrival angles first for the clusters and then for the rays of which the clusters are composed. When all large- and small-scale parameters are set, the final MIMO channel impulse response coefficients are calculated.

The SSE-MACHINE implements generation of LSPs and SSPs together with final calculation of channel impulse response. The IMT-A-MACHINE implements the network layout and deployment and together with SSE-MACHINE constitute the IMT-Advanced evaluation framework for simulation based assessment of 4G candidate technologies. SSE-MACHINE is also utilized by MGM-MACHINE.

IV. MANHATTAN/MADRID GRID MODEL

One of the REM part of the MACHINE is the Madrid Grid Model (MGM) which is an implementation of the environment and channel models defined in the METIS project [4,7,18].

The METIS project channel models are defined as so-called propagation scenarios (PS). These propagation scenarios can be divided into three sub-groups based on transmitter’s and receiver’s locations. These are:

- outdoor-to-outdoor (O2O) propagation,
- outdoor-to-indoor (O2I) propagation,
- indoor-to-indoor (I2I) propagation.

These three sub-groups of propagation scenarios can be further divided depending on the type of the communication link. Three types of links are recognized, i.e. macro base station (MaBS) to user equipment (UE) links, micro base station (MiBS) to UE links and UE to UE links. The MaBS to UE link propagation scenarios correspond to a situation where the BS is located over a building rooftop. The MiBS to UE link propagation scenarios are defined for BSs located below the buildings’ rooftops where the dominant part of the propagation is due to the reflections between buildings. The UE to UE link is defined to model the propagation for the device-to-device (D2D) communication.

In the MGM, eight propagation scenarios are identified:

- PS#1 Urban Micro Outdoor-to-Outdoor
- PS#2 Urban Micro Outdoor-to-Indoor
- PS#3 Urban Macro Outdoor-to-Outdoor
- PS#4 Urban Macro Outdoor-to-Indoor
- PS#7 Indoor Office
- PS#9 D2D Urban Outdoor-to-Outdoor (also for Vehicle-to-Vehicle),
- PS#10 D2D Urban Outdoor-to-Indoor,
- PS#13 D2D Indoor Office.

The propagation scenarios were defined with two important assumptions in mind. Firstly, a realistic and not synthetic scenario is required. Secondly, a 3D propagation model should be utilized in system evaluations. In the currently commonly used propagation models, the LoS or NLoS conditions are randomly selected. However, for scenarios that are realistic, the sight conditions between transmitter and receiver should be evaluated on a real-time basis. A more detailed description of propagation scenarios can be found in [18]. Fig. 2 contains examples of some of the defined PSs.

The PS could not exist without a suitable environment model. For this purpose a Madrid Grid (MG) environment model has been defined. The MG is a realistic urban environment model. The realism is achieved by considering different environments of buildings, roads, parks, bus stops, metro entrances, sidewalks and crossing lanes. The model is based on the structure of Madrid and captures typical European city characteristics. Fig. 3. presents the streets and buildings layout of the MG along with the BSs deployment [4].

The MACHINE fully implements the channel, environment and the mobility model defined in the D6.1 of the METIS.
project. The detailed description can be found in [18]. One of the more interesting features of the implementation of the MGM is the possibility of creating a custom city layout and modeling the channel with METIS propagation scenarios. In [7] we presented a results of simulations performed based on Poznań Old Market.

Fig. 2. MGM propagation scenarios [7].

Fig. 3. MGM environment model [4].

V. LTE-BASED LINK LEVEL SIMULATOR

The first tool developed within MACHINE simulation framework was the Long Term Evolution (LTE) link level simulator. It models a single or multiple communication links that can be established between network nodes such as base stations, mobile stations and relay stations. The LTE-LLS implements a complete LTE transport and physical layer processing procedures. In case of the data transmission the DL-SCH (transport layer) and the PDSCH (physical layer) channels are simulated. DL-SCH transport channel processing is a combination of error detection, error correction, rate matching, interleaving and transport channel mapping onto the PDSCH physical channel. Forward error correction (FEC) is provided by the turbo code, and error detection is based on cyclic redundancy check (CRC) codes. If the block size at the input of the turbo code encoder is greater than $Z$ equal to 6144 bits, code block segmentation is performed. The rate matching performs interleaving, as well as repetition or puncturing, in order to match the size of a block generated at the output of the transport channel to the number of bits allocated for the transmission of the physical channel. The number of bits carried by the PDSCH physical channel is determined by the modulation scheme, the number of resource blocks allocated for transmission, and the transmission mode. PDSCH processing consists of scrambling, modulation, layer mapping, precoding, mapping onto resource grid and conversion to complex-valued OFDM baseband signals for each antenna port. These antenna ports do not correspond to physical antennas, but rather are logical entities distinguished by their reference signal sequences. Multiple antenna port signals can be transmitted on a single transmit antenna. Correspondingly, a single antenna port can be spread across multiple transmit antennas. Both layer mapping and precoding are associated with multiple antenna transmission and reception (MIMO).

These two steps map up to two incoming code words to up to four transmit antennas (LTE Rel. 8). At the receiver side, complementary operations are performed after channel estimation and data equalization.

The LTE-LLS consists of several parts. Fig. 4 presents the top-level architecture of the LTE link level simulation package implementation [2]. The core processing is written in C++ programming language in an object oriented way. This main part utilizes IT++ library [13], which is a C++ library of mathematical, signal processing, and communication classes and functions. The validation of the core part source code is done by unit testing. Unit tests of the main project modules are placed in a separate C++ project. Unit testing gives the ability to verify that implemented methods works as expected for any given set of inputs by returning the proper values or handling failures (in case of invalid input). The testing project uses one of the most commonly used C++ unit testing framework - the Google Test (GTest) [14].

The performance of the LTE link level simulator was aligned with the results obtained by 3GPP partners during the design of the LTE system. We compared our results with [19] where ideal simulation results for PDSCH in AWGN channel are presented. After that we configured our simulation tool according to [20] where UE demodulation simulation assumptions were agreed by 3GPP partners. The obtained results were compared with those presented in [21].

The more detailed description of the developed LTE-based link level simulator can be found in [2].

<table>
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Fig. 4. LTE link level simulation package structure [2].
VI. LINK-TO-SYSTEM INTERFACE

Due to excessive processing involved in determining the result of a transmission of a data block through the mobile radio channel it is practically not realistic to perform it for each link in the radio network. Therefore proper abstraction of a single link transmission is needed in order to limit the processing requirements. Typically from the current channel impulse responses of the desired and interfering links a single metric is constructed that enables to map this conditions onto block error probability. Several methods were developed for this purpose. L2S-MACHINE utilized the mutual information effective SINR mapping (MIESM) approach.

VII. LTE-BASED SYSTEM LEVEL SIMULATOR

Even though SLS-MACHINE is based on the LTE technology it is able to simulate features beyond the current specification of the LTE standards. Apart from typical simulation setups with cellular network consisting of base stations (BSs) and mobile stations (MSs), it is capable of simulating two-way relaying and D2D scenarios.

In principle SLS-MACHINE was designed to simulate orthogonal frequency division multiple access (OFDMA) based systems. The tool models algorithms and procedures of such a system utilizing interfaces provided by one of the REMs described before and L2S interface. There are four primary operations that are realized by SLS. First, based on the feedback received from various elements of the radio network, scheduling is performed. Scheduling distributes time, frequency, power, and space (MIMO streams) resources between radio transmission capable nodes. Based on these assignments, appropriate links are updated by calculating channel impulse responses preceded by terminals position update if required. After that calculation of post-reception signal to interference and noise power ratios can be realized.

In OFDMA-based systems interference pattern changes in each transmission time interval (TTIs) due to the dynamic scheduling. This pattern is specific to used transmission protocols, devices, and their operation modes (eg. D2D, two-way relaying). Finally, feedback metrics can be calculated. This step can involve, calculation of effective SINR, channel quality indicators CQIs, precoding matrices indices (PMIs), determination of positive or negative acknowledgements (ACK/NACKs), and rank indicators (RIs) to name a few. During the simulation various statistics are calculated and collected.

VIII. CONCLUSIONS

Development of comprehensive simulation platform is a challenging task. It requires vast knowledge of various elements of complex radio systems. The development of MACHINE is a result of the shared expertise of its authors in various aspects of wireless communication technology, ranging from radio propagation and environment modeling (both stochastic and ray-tracing methods), through physical layer processing algorithms (including MIMO processing) and scheduling algorithms, up to the standards knowledge. These team effort continues along the research on 5G systems. Current work is mainly concentrated on the system level aspects.

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