Study of Throughput in 3GPP LTE Systems by Means of Analytical and Simulation Models

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***Abstract*—Long Term Evolution (LTE) system is developed by the 3rd Generation Partnership Project (3GPP), where Release 10 named LTE-Advanced is submitted as one of the candidates of IMT-Advanced systems to International Telecommunications Union-Radiocommunications (ITU-R) for evaluation. In this work, an analytical as well as a simulation model are elaborated to calculate the system capacity distribution, error ratio distribution and throughput distribution for different types of scenarios in LTE-Advanced systems.**

I. Introduction

International Telecommunications Union-Radiocommunications (ITU-R) Sector Working Party 5D defines International Mobile Telecommunications-2000 (IMT-2000) and IMT-Advanced systems, which correspond to 3G and 4G systems. Long Term Evolution (LTE) system is developed by the 3rd Generation Partnership Project (3GPP), where Release 8 and 10 are submitted as one of the candidates of IMT-2000 and IMT-Advanced systems to ITU-R for evaluation. The latter release is named LTE-Advanced. It takes ITU-R requirements as basis.

Multiple evaluation groups supported the IMT-Advanced process to verify the performance results [1] of IMT-Advanced candidate systems. System level simulation and analytical modeling are possible methods to evaluate the performance of complex systems. Simulation models may experience problems like excessive simulation run time, some not so realistic parameter settings, unanticipated implementation errors, etc. Analytical models may require a too high degree of abstraction of the real system, possibly invalid modeling assumptions and parameter settings, etc. To guarantee comparable performance results and agree on common assumptions, [2] serves as a common baseline reference configuration for LTE-Advanced systems.

In this paper, an analytical framework is presented to evaluate system capacity of different protocol layers in 3GPP LTE systems. It is assumed that User Terminals (UTs) are randomly and uniformly distributed over the whole service area and that the system is loaded with full buffer traffic. Furthermore, a simulation model for LTE based on the open Wireless Network Simulator (openWNS) is also introduced. It can calculate the station throughput under a given traffic load and a certain number of UTs.

In Section II, an analytical model based on Signal Flow Graph is introduced. In Section III, capacity of Radio Link Control (RLC) layer is analyzed for the Urban Macro-cell (UMa) scenario [2] as an example. In Section IV, a detailed simulation model for LTE implemented based on the simulator openWNS is presented. The simulator was calibrated in the Wireless World Initiative New Radio+ (WINNER+) project [3]. In Section V, stochastic, event driven system level simulations are performed in two different IMT-Advanced predefined scenarios, not only the Indoor Hotspot scenario (InH) but also the UMa scenario, for example. Section VI concludes this work.

A. Brief Introduction to LTE System

The protocol stack of LTE system [4] consists of the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC) and PHYsical layer (PHY). PDCP performs IP header compression to reduce the number of bits to be transmitted over the radio interface. RLC is responsible for the segmentation and concatenation of IP packets, retransmission of erroneously received PDUs and in-sequence delivery of Service Data Units (SDUs) to upper layers using Selective Repeat - Automatic Repeat reQuest (SR-ARQ). MAC handles logical channel multiplexing, Hybrid-ARQ (H-ARQ) retransmission, uplink and downlink scheduling, where H-ARQ is a combination technology of Forward Error Correction (FEC) and ARQ. PHY handles coding and decoding as well as modulation and demodulation.

The basic transmission scheme for downlink in LTE is Orthogonal Frequency Division Multiplex (OFDM). OFDM subcarrier spacing for downlink and uplink is 15 kHz. Transmission takes place in time and frequency domains. In the time domain, each frame has the time duration of 10 ms and contains 10 subframes. Each subframe lasts 1 ms and contains 2 time slots. Suppose normal cyclic prefix is used, then there are 7 OFDM symbols in each time slot. The smallest physical resource in LTE is a *resource element*, which consists of one subcarrier during one OFDM symbol. A *resource block* (RB) is defined as 12 consecutive subcarriers in frequency domain and one slot with 0.5 ms in the time domain. With normal cyclic prefix, 84 resource elements are contained in one resource block. The minimum scheduling unit is *physical* *resource block pair* (PRBP). It contains two time-consecutive RBs within one subframe. In the frequency domain, the LTE system bandwidth can vary from 6 RBs to 110 RBs, that implies bandwidth varies from 1.08 MHz to 19.8 MHz. Not all resource elements can be used for data transmission. Some must be reserved for control information and reference signals. They are considered as overhead. Frequency Division Duplex mode (FDD) will be studied by the analytical as well as the simulation model. The physical broadcast channel is located in the first subframe and within the 6 RBs of the middle frequency band. The synchronization sequences are located in the first subframe and the sixth subframe in the time domain and within the 6 RBs of the middle frequency domain. The first three OFDM symbols of each PRBP in the frame are occupied by downlink control channels, i.e. the Physical Control Format Indicator CHannel (PCFICH), Physical Hybrid-ARQ Indicator CHannel (PHICH) and Physical Downlink Control CHannel (PDCCH). Only one antenna port for downlink is considered in this work, therefore eight REs per PRBP are reserved by cell specific reference symbols.

B. IMT-Advanced evaluation methodology

ITU-R defines some minimum requirements of performance parameters to ensure IMT Advanced technologies fulfilling objectives of IMT-Advanced [1]. IMT-Advanced systems support low to high mobility applications and a wide range of data rates in accordance with user and service demands in multiple user environments. To set a specific level of minimum performance, that must be achieved by each proposed technology, evaluation guidelines for evaluation procedure and criteria are defined by ITU-R to be used in assessing IMT-Advanced systems [2]. Four test environments and their corresponding deployment scenarios are defined for evaluation. They are the InH scenario, the UMa scenario, the Urban Micro-cell (UMi) scenario and the Rural Macro-cell (RMa) scenario, where InH and UMa scenarios will be introduced in details. They will be analytically evaluated and assessed using system level simulation.

II. Analytical Framework

A non-conventional framework, namely signal flow graph (SFG) models for PHY, MAC and RLC layers, is applied for analyses, Fig. 1. Thereby, various aspects of the different LTE system layers can be modeled for calculating capacity and error ratio.

On PHY layer, probabilistic radio channel states, association of user equipments (UEs) to radio access points (RAPs), turbo coded M-QAM block error rate (BLER), adaptive modulation and coding (AMC), Chase combining (CC) and overhead in LTE radio frame are taken into account. On MAC layer, hybrid ARQ (H-ARQ) protocol, unreliable resource assignment and unreliable feedback are accounted for, where number of maximal retransmissions, probability of resource assignment failure and probability of feedback misdetection can be parameterized, respectively. On RLC layer, segmentation of a RLC SDU into several RLC PDUs, selective repeat

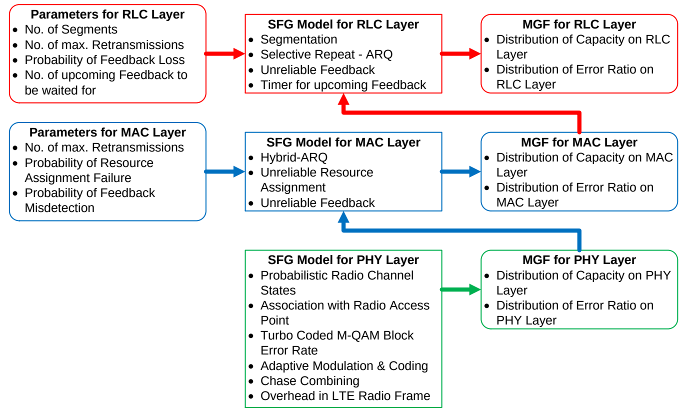

Fig. 1. Analytical framework

ARQ (SR-ARQ) protocol, unreliable feedback and timer for feedback are considered with number of segments, number of maximal retransmissions, probability of feedback loss and number of upcoming feedbacks to be waited for as parameters, respectively.

Moment generating functions (MGFs), that represent probability distributions of the resources consumed to transmit PHY transport block, MAC SDU and RLC SDU, can be derived from SFGs, that are able to analyze the transmission process on each layer step by step in detail. Based on MGF of a certain layer for an arbitrary small area element, the probability distributions of capacity and error ratio on the respective layer can be determined for this area element. The probability distributions of capacity and error ratio for a cell can be aggregated from the probability distributions for all area elements in the whole cell. The SFGs of RLC and MAC layers are modeled on the basis of the MGFs of MAC and PHY layers, respectively.

SFG models and MGFs of PHY, MAC and RLC layers as well as probability distributions of capacity and error ratio have been published already in [5]. Therefore, only the SFG model for RLC layer and its corresponding MGF as well as how to evaluate probability distributions of capacity and error ratio based on MGF are repeated, and the others are omitted here.

A. Signal Flow Graph Model

According to the SR-ARQ protocol [6], an example SFG for RLC layer is shown in Fig. 2. Without loss of generality, it is assumed that 1 RLC SDU is segmented into 2 RLC PDUs and retransmission is ACK based. The model is generally applicable to M segments and NAK based systems. Similar to the SFG for MAC layer, the SFG for the transmission of RLC SDU is specified as a recursion.

Firstly, the 1^{st} segment is either transmitted successfully or unsuccessfully on MAC layer. Secondly, the transmission of the 2^{nd} segment either succeeds or fails. Thirdly, the ACK feedback for the correctly transmitted segment is received or lost, where p_{LOSS} stands for the probability of ACK loss.

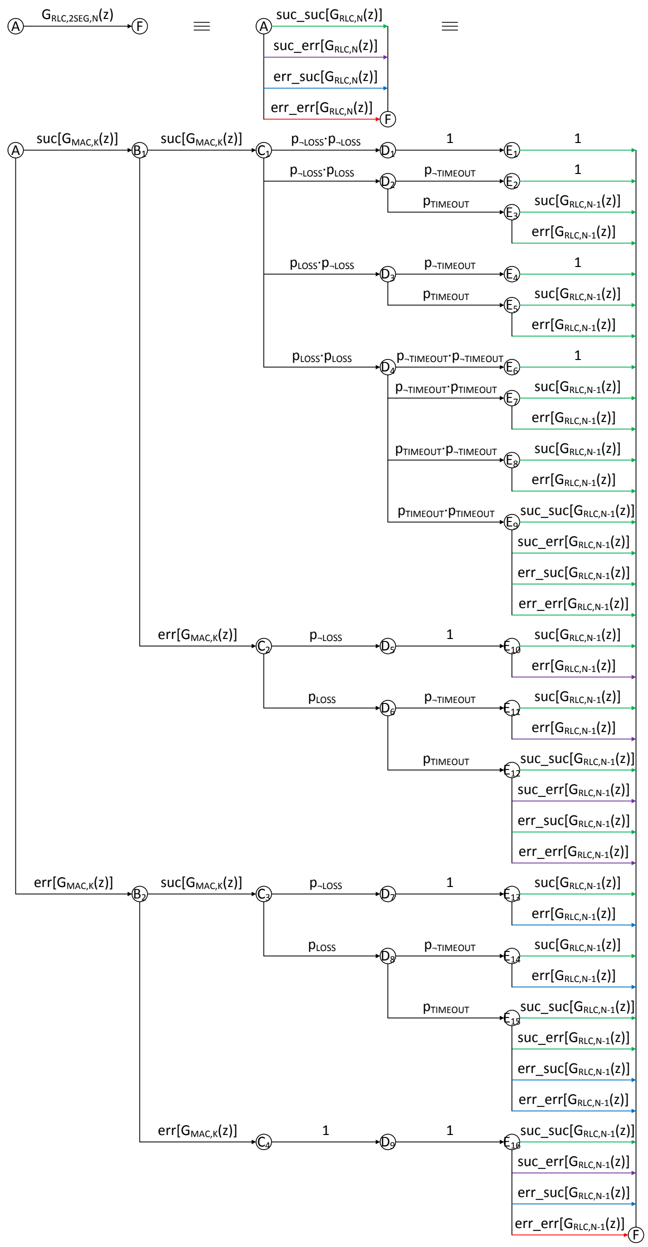

Fig. 2. SFG for RLC layer: recursion for 2 segments

Fourthly, the timer supervising upcoming feedbacks in case of ACK loss is either run out or not, where $p_{TIMEOUT}$ stands for the probability of timer expiration. Finally, retransmission is carried out for erroneously transmitted segments and for the segments, which are correctly transmitted but experience ACK loss and timer expiration. There is no retransmission assumed for all the other cases.

The transmission of a certain segment succeeds, if the corresponding MAC SDU is correctly transmitted on MAC layer, or the transmission on MAC layer is unsuccessful but one of the next retransmissions is successful. The transmission of the segment fails for all the other cases. Similar to the SFG

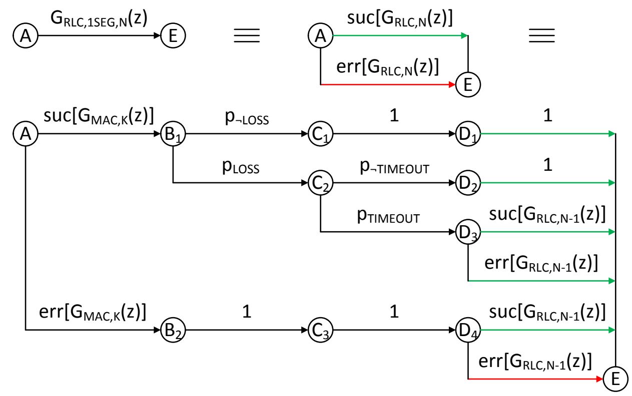

Fig. 3. SFG for RLC layer: recursion for 1 segment

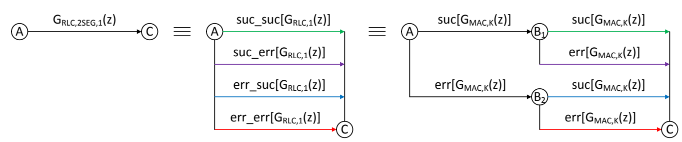

Fig. 4. SFG for RLC layer: exit condition for 2 segments

for MAC layer, a path is classified to the green group, if both segments are successfully transmitted, or to the purple group, if the 1^{st} segment is transmitted correctly but the 2^{nd} one is in error, or to the blue group, if transmission of the 1^{st} segment is erroneous but the 2^{nd} one is correct, or to the red group, if both transmissions are unsuccessful. Merely the green group represents a successful transmission of RLC SDU, while all the other groups represent an erroneous transmission.

There is the case in retransmissions, that only one of the both segments is transmitted. The SFG for the transmission of 1 segment is shown in Fig. 3.

As exit conditions for the recursions, the SFGs for the transmission of 2 segments and 1 segment within only 1 transmission on MAC layer are shown in Fig. 4 and Fig. 5, respectively.

B. Moment Generating function

The MGF for the exit condition can be derived from the SFG. The parts corresponding to green, purple, blue and red groups are given as follows, respectively.

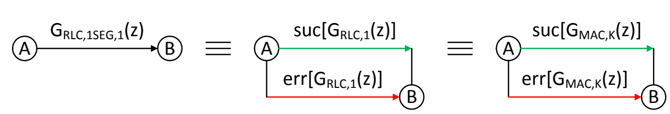

Fig. 5. SFG for RLC layer: exit condition for 1 segment

$$G_{RLC,2SEG,1}(z) = suc\_suc[G_{RLC,1}(z)] + suc\_err[G_{RLC,1}(z)] + err\_suc[G_{RLC,1}(z)] + err\_err[G_{RLC,1}(z)] \quad (1)$$

$$suc\_suc[G_{RLC,1}(z)] = suc[G_{MAC,K}(z)] \cdot suc[G_{MAC,K}(z)] \quad (2)$$

$$suc\_err[G_{RLC,1}(z)] = suc[G_{MAC,K}(z)] \cdot err[G_{MAC,K}(z)] \quad (3)$$

$$err\_suc[G_{RLC,1}(z)] = err[G_{MAC,K}(z)] \cdot suc[G_{MAC,K}(z)] \quad (4)$$

$$err\_err[G_{RLC,1}(z)] = err[G_{MAC,K}(z)] \cdot err[G_{MAC,K}(z)] \quad (5)$$

The MGFs for the recursions can also be obtained from the SFGs straightforwardly but are omitted here.

C. Capacity and Error Ratio

For each layer, the MGF and the part corresponding to an erroneous transmission of SDU are generally expressed as follows.

$$G_{Layer}(z) = \sum_{i=1}^{N} (p_i \cdot z^{\#PRBP_i}) \quad (6)$$

$$err[G_{Layer}(z)] = \sum_{i=1}^{N} (e_i \cdot z^{\#PRBP_i}) \quad (7)$$

The probability distributions of capacity and error ratio can be derived from the MGF. The capacity in the i^{th} channel state is mapped from $\#PRBP_i$ and the probability to achieve this capacity is p_i.

$$Prob[Capacity[bps] = \frac{Bandwidth}{\#PRBP_i} \cdot Payload \cdot 10^3] = p_i, i = 1, 2, ..., N \quad (8)$$

The error ratio in the i^{th} channel condition is exactly e_i/p_i and the probability to experience this error ratio is p_i.

$$Prob[ErrorRatio = \frac{e_i}{p_i}] = p_i, i = 1, 2, ..., N \quad (9)$$

TABLE I
PARAMETERS OF UMA SCENARIO

scenario	**urban macro-cell (UMa)**
layout	hexagonal grid
inter-site distance	500 m
BS antenna height	25 m, above rooftop
# BS antennas	1 tx
total BS transmit power	46 dBm for 10 MHz
BS antenna down tilt angle	12°
UE antenna height	1.5 m
# UE antennas	1 rx
minimum distance between UE and BS	≥ 25 m
carrier frequency	2 GHz
channel model	UMa (LoS, NLoS)
BS noise figure	5 dB
UE noise figure	7 dB
BS antenna gain(boresight)	17 dBi
UE antenna gain	0 dBi
thermal noise level	-174 dBm/Hz

III. PERFORMANCE CALCULATION

The urban macro-cell (UMa) scenario [2] is considered here with parameters given in Table I.

Referring to the hexagonal grid layout shown in Fig. 6, one base station (BS) is placed in the center of the scenario and one tier of six BSs are placed around for interference consideration. Three antennas are employed by each BS at 30°, 150° and 270°, respectively. The area served by a BS is termed as a site and the area served by an antenna is referred to as a cell.

According to the UMa channel model, path loss is specified for both, line of sight (LoS) and non LoS (NLoS) conditions, where the probability of LoS is defined as a function of distance. As illustrated in Fig. 6, a UE on downlink receives signals from its serving base station (BS) and simultaneously cochannel interference from up to six neighbor BSs. Both links, between serving BS and UE and between interfering BSs and UE, may result from either LoS or NLoS radio propagation.

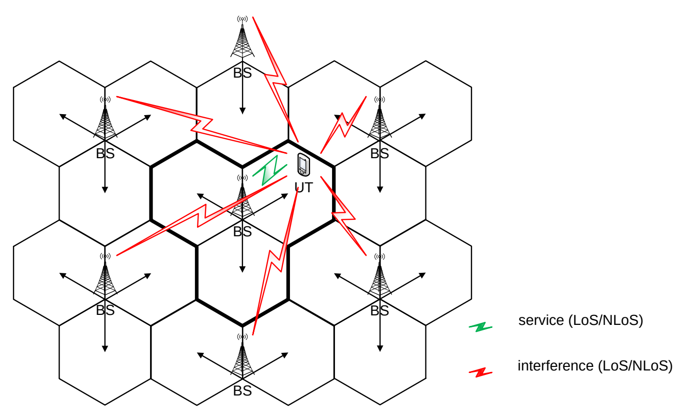

Fig. 6. Hexagonal grid layout

With the described SFG models, cumulative distribution functions (CDFs) of capacity and error ratio on each layer can be computed for each position of an UE. The mean value of capacity and error ratio at a certain UE position in the scenario can be obtained straightforwardly from the respective CDF valid for this position. Considering that UEs are randomly and uniformly distributed over the whole service area, a CDF of capacity and error ratio for a cell can be derived from CDFs for all positions over the cell.

Capacity and error ratio are assessed from multi-cell scenario map with expected value for each location and CDF for a cell. Results for PHY, MAC and RLC layers have already been given in [5]. Hence, only results for RLC layer are repeated and the others are omitted here.

A. Scenario Map

For scenario maps of capacity and error ratio on RLC layer, the LTE system is configured as follows. On MAC layer, maximal 1 retransmission is permitted for the H-ARQ protocol. Neither resource assignment failure nor feedback misdetection is taken into account. On RLC layer, 1 RLC SDU is segmented into 2 RLC PDUs and maximal 1 retransmission is permitted for the SR-ARQ protocol. Neither feedback loss nor timer for upcoming feedbacks is taken into consideration. The RLC SDU is assumed to be 1024 bytes. RLC header, MAC header and PHY cyclic redundancy check (CRC) are 4 bytes, 3 bytes and 3 bytes, respectively.

The mean capacity on RLC layer for each UE (x, y) coordinate in the center site of UMa scenario is shown in Fig. 7. The antenna boresight areas and the areas nearby the BS have the highest capacity due to the best radio propagation condition. The site edge, the borders between adjacent cells and the area close to the BS suffer from the lowest capacity because of strong cochannel interference from neighbor BSs and adjacent cells, respectively. The mean error ratio on RLC layer for each UE position in UMa scenario is shown in Fig. 8. The site edge suffers from high error ratio, while the borders between adjacent cells and the area close to the BS are not troubled much.

B. CDF for a Cell

For CDFs of capacity and error ratio on RLC layer, the following 4 different configurations are used. For all cases, 1 RLC SDU is segmented into 2 RLC PDUs and the retransmission mechanism is ACK based. There is no retransmission in blue case, while maximal 1 retransmission can be performed in the other cases. The probability of feedback loss, including ACK loss and NAK loss, is assumed to be 0% in red case, and 10% in green and pink cases. The timer is deactivated in green case, while for the lost ACK feedback 1 upcoming feedback is assumed to be waited for in pink case.

The CDFs of capacity and error ratio on RLC layer are shown in Fig. 9 and Fig. 10, respectively. In red case, the error ratio is strongly decreased in comparison to blue case, since retransmission is performed to correct the residual error from MAC layer, and the capacity is slightly deteriorated, since the retransmission results in additional resource consumption and the residual error from MAC layer is quite low. In green case, retransmission is performed for not only the residual error from MAC layer but also the lost ACK feedback on RLC layer in ACK based system. The capacity is obviously deteriorated in comparison to red case, since the retransmission due to feedback loss leads to distinct resource waste. The error ratio is identical with that of red case, because in ACK based system the feedback loss does not impact on the error ratio. In pink case, the capacity is significantly improved in comparison to green case and is only a little bit lower than that of red case, since the timer is activated to avoid resource waste and compensates almost all the effect of feedback loss. The error ratio is identical with that of green case, because in ACK based system the timer has no effect on the error ratio.

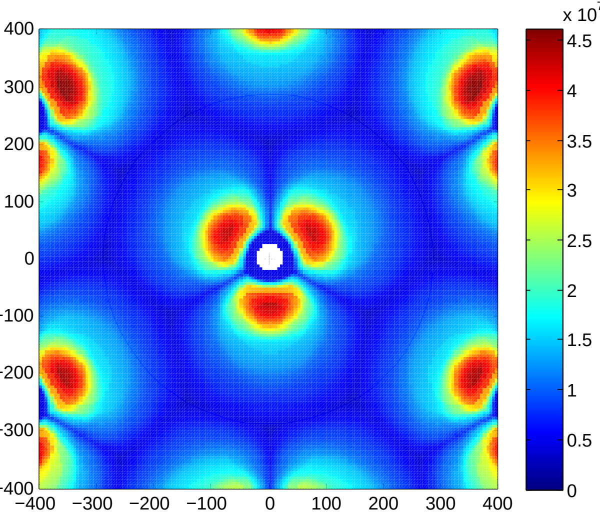

Fig. 7. Mean capacity on RLC layer for (x,y) in scenario

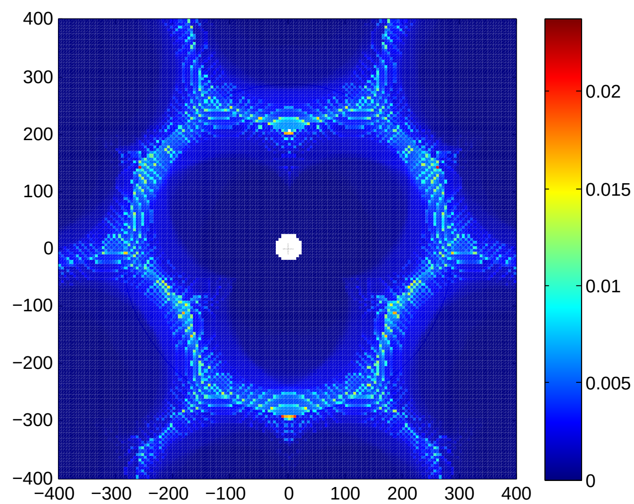

Fig. 8. Mean error ratio on RLC layer for (x,y) in scenario

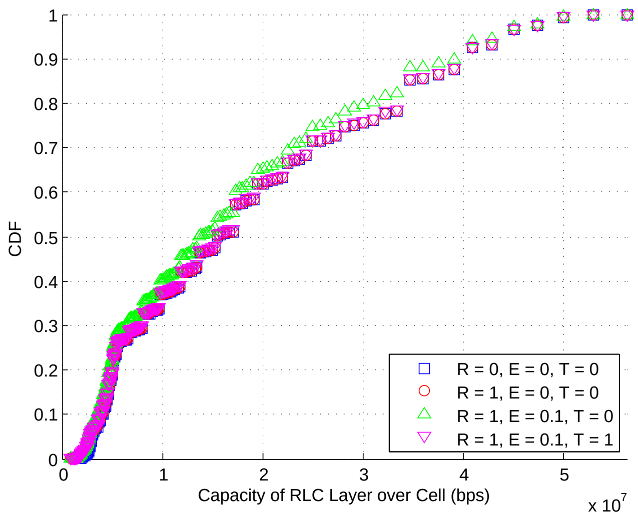

Fig. 9. CDF of capacity on RLC layer for configurations

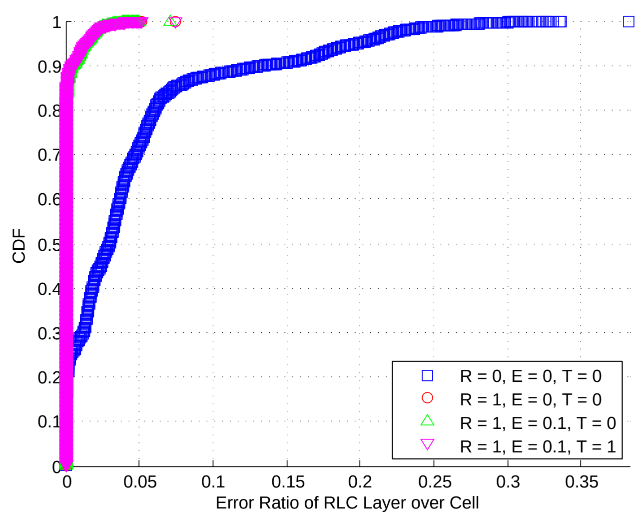

Fig. 10. CDF of error ratio on RLC layer for configurations

IV. Simulation Model

Open Wireless Network Simulator (openWNS) has been developed by Communication Networks (ComNets) Research Group at RWTH Aachen University. It is an IMT-Advanced compliant system level simulation tool. Its core is written in C++ and scenarios are configured in Python. It contains detailed interference modeling, IMT-Advanced channel models, mobility models, traffic load generators and statistical evaluation methods. It was calibrated in the European WINNER+ project, in which different WINNER+ project partners cooperated to evaluate LTE-Advanced performance [3].

A. Fundamentals of openWNS

openWNS [7] [8] [9] is able to simulate not only simple queueing systems but also complex wired or wireless communication systems. In the latter case, a simulation model can contain several kinds of stations in one scenario, e.g. base stations, mobile stations and relay stations. Each station is represented by one Node class. Each Node contains a set of Components, which represent the protocol layers of ISO/OSI reference model. Such a component-based development approach makes development of simulation models and often used parts of protocol stacks easy to implement and easy to configure. *Functional Unit* (FU) is defined as basic building block of a protocol stack. It implements a single function und allows a high degree of reuse. FUs are interconnected to form *Functional Unit Networks* (FUNs) to jointly fulfill tasks of protocol layers.

Each FU provides three generic interfaces, via which FUs can communicate with each other. They are the data handling, flow control and management interfaces. The most fundamental request for FU is to handle data. The *Data Handling Interface* must be able to receive data for processing before and after the data units are transmitted over air-interface. The first case is outgoing data flow and the latter is incoming data flow. sendData() and onData() are the corresponding methods called by the upper FU in outgoing data flow and the lower FU in incoming data flow, respectively. These methods are called to propagate data through FUN. Sometimes, FUs may want to prevent other units from delivering data to them. Possible reasons are limited capacity to store data or no need at all to store. *Flow Control Interface* with isAccepting() and wakeup() methods are designed for this purpose. Before the upper FU can deliver data to the lower FU, it must make sure the target FU is willing to accept via isAccepting(). The lower FU is able to stop data flow if it is not able to accept any more. Asking for permission for each concrete data unit is necessary, because the decision is based on its content, e.g. concatenation unit may accept small compound, but have no capacity left for a larger one. When the upper FU is not able to deliver further data units, it must cease the operation until it is triggered again. wakeup() is called by lower FUs to indicate that it is accepting data again. *Management Interface* is responsible for managing composition and configuration of FUN. Two example methods are connect() and onFUNCreated(). They are called to connect two FUs und to signal successful creation of FUN, respectively. Custom interface is not mandatory to each FU. But it is beneficial for FUs in terms of providing more information about the internal state of a FU. For example the getLength() of a FU named Buffer, one certain buffer may be preferred over others, if its length exceeds a certain threshold.

Each FU must define Connector set, Deliverer set and Receptor set in it. Connector set contains a set of lower FUs that data units will be delivered to in outgoing direction. FU calls sendData() method of lower FUs in their Connector set to pass on data units to those FUs. Deliverer set is composed of a set of upper FUs in incoming direction. FU calls onData() method of upper FUs in their Deliverer set to pass on data units to them. Receptor set consists of a set of upper FUs, where the FU itself is in their connector sets. To wakeup upper FUs, lower FUs must call wakeup() method of upper FUs in their Receptor set. A FUN is constructed by defining FUs,

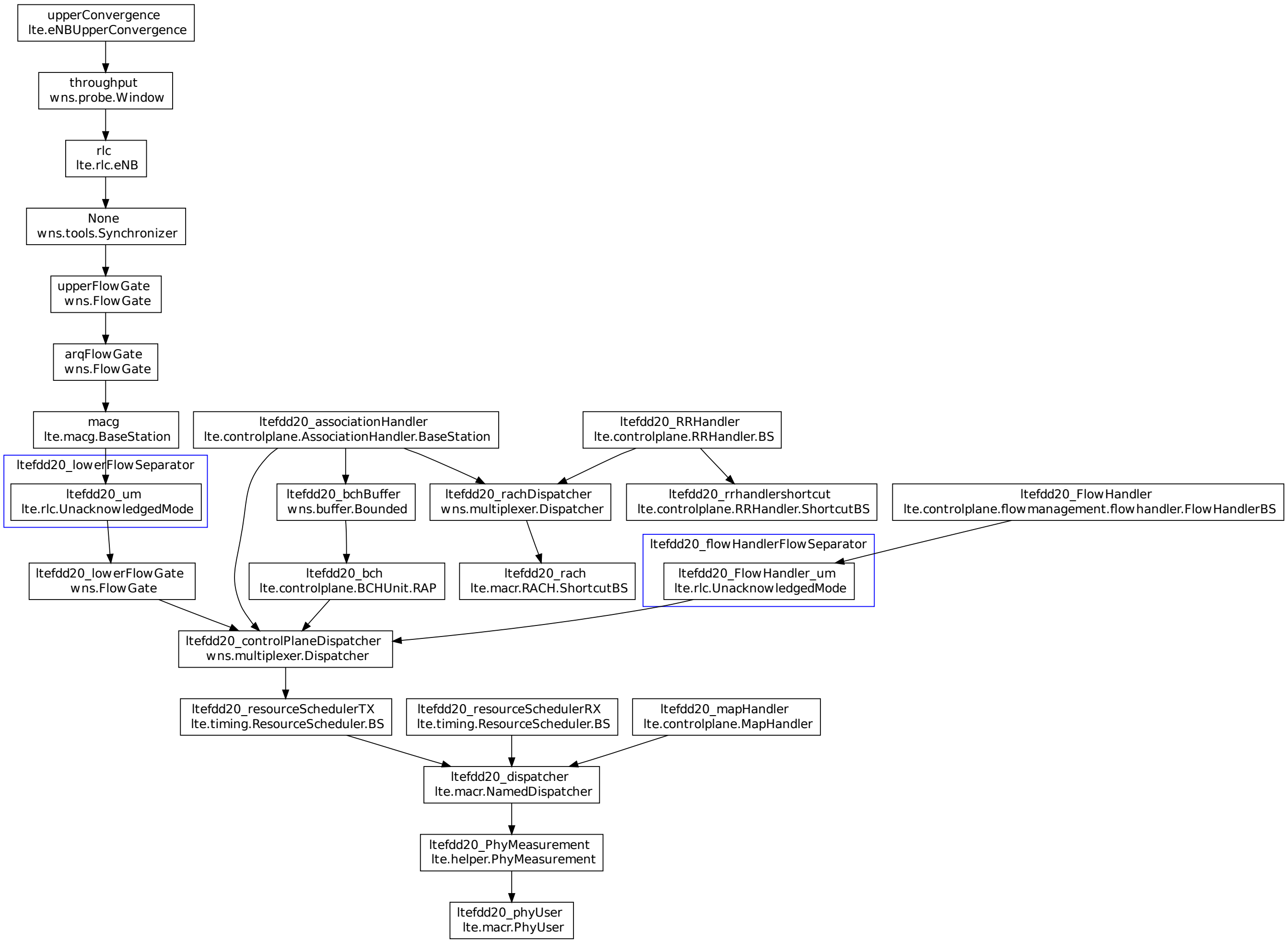

Fig. 11. eNodeB DLL functional unit network

connecting them, identifying their Connector, Deliverer and Receptor sets, designating a set of FUs as sink for outgoing flows and as sink for incoming flows.

Another important characteristic of FU is the ability to add control information. For example, ARQ FU must be able to add sequence numbers as control information to outgoing data units. Control information added by FU is called command in openWNS. It is required that commands can be accessed by lower FUs or FUs in a peer FUN. A command pool is defined as a set of all commands added by every FU within a FUN. Compound is defined as the union of a data unit and the command pool. Thus, compound can be seen as protocol data unit (PDU) and command pool as protocol control information (PCI).

B. FUN of eNodeB and UT in LTE-Module

The LTE module [10] is currently implemented as part of openWNS for performance evaluation of LTE systems. Fig. 11 shows how the functionality of the Data Link Layer (DLL) of LTE system can be composed of a number of FUs. It shows the FUN of DLL layer in eNodeB. The used FUs can be divided into two different categories, i.e. common, system-independent fuctions and LTE specific functions.

The first category can be taken from a toolbox of generic protocol functions. These can also be used to implement protocol stacks for other communication systems. Examples are: Synchronizer, FlowGate, BoundedBuffers, Dispatcher, etc. Synchronizer is used to force the synchronization of the command pool. Gate provides two interfaces: setIncomingState(State) and setOutgoingState(State), where State can be either OPEN, or CLOSED. In the incoming data flow, if the upper FU can no longer accept any compounds, the only option is to drop the compounds. All compounds will be dropped when the incoming state is set to CLOSED. In the outgoing data flow, intra layer flow control is used to prevent compounds from being delivered. This flow control is achieved by means of using isAccepting(). Bounded belongs to the class Buffer. It uses intra layer flow control to keep FUs from delivering compounds when the maximum fill level has been reached. Compounds, whose size exceeds the total remaining size of the buffer, will never get accepted. Dispatcher is used to join paths in outgoing data flows of a FUN and to guarantee the path preserving delivery in the incoming data flow of the peer FUN. In the outgoing data flow, the Dispatcher multiplexes compounds from multiple upper FUs to a single lower FU. In the incoming data flow, it guarantees to deliver compounds to the same FU, from which they have been received in the outgoing data flow.

The second category is specially designed in the LTE module. It is further divided into three groups, for eNodeB, for User Terminal (UT) and for control plane. It includes IP Convergence Layer, rlc, macr, Flow Handler, Association Handler, bch, rach, Measurement, macg, etc., where macr performs the actual mapping of data flows onto physical resource blocks and macg is responsible for addressing and QoS control.

C. Simulation Scenarios in LTE Module

The Indoor Hotspot (InH) scenario is the default setup in the simulator. According to [2], it targets isolated cells at offices and/or in hotspot, based on stationary and pedestrian users. It focuses on smallest cells and high user throughput in buildings. The scenario consists of one floor of a building shown in Fig. 12. The height of the floor is 6 m, containing 16 rooms R_1, R_2, ..., R_{16} of $15m \times 15m$ and a long hall of $120m \times 20m$. Two sites S_1 and S_2 are placed in the middle of the hall at 30 m and 90 m, which implies that inter-site distance (ISD) is 60 m. Center carrier frequency for evaluation is set at 3.4 GHz. The simulation bandwidth is 20 MHz for uplink and 20 MHz for downlink in FDD. UT speed of interest is 3 km/h.

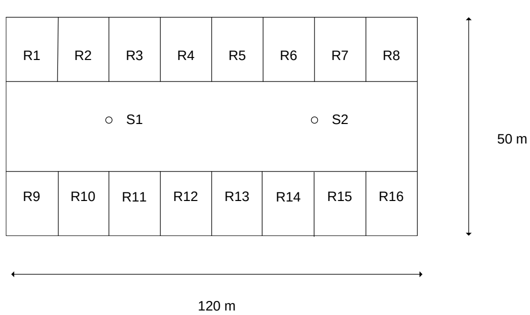

Fig. 12. Indoor Hotspot Scenario

The Urban Macro-cellular (UMa) environment as shown in Fig. 13 is evaluated in the analytical model in Section III. According to [2], it targets continuous coverage for pedestrian up to fast vehicular users. It focuses on large cells and continuous coverage. Fixed base station antenna is clearly above surrounding building heights. Typical building heights are over four floors. Mobile stations are located outdoors at street level. Radio propagation conditions are usually non-line-of-sight, since street level is often reached by a single diffraction over the rooftop. Carrier frequency for evaluation is set to be 2 GHz. The simulation bandwidth is 20 MHz for downlink and 20 MHz for uplink in FDD. UT speed of interest is 30 km/h. Inter-site distance is 500 m.

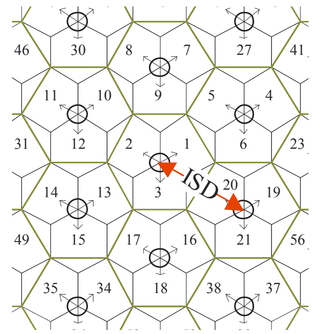

Fig. 13. Urban Macro Scenario

V. SIMULATION RESULTS

LTE Release 8 simulator configurations in [2] are used in the current LTE module. The baseline calibration setup reuses the cell spectral efficiency setup as specified by the ITU-R and deploys an LTE Release 8 system operating in FDD mode [10]. InH scenario is the default configuration and UMa scenario is not configured at all in the current LTE-module. In this work, it is newly configured to obtain some interesting performance results.

A. Simulation Settings in InH Scenario and Results

The simulation for InH is implemented in openWNS [10]. But the simulation can only be run locally. That means, simulation results are only available in plain text and are not visualized. Some Python script must be written to create a parameter file. It contains the parameters that differentiate the simulations from each other. With this Python script, the simulation results are written to the database integrated in Wireless network simulator Result brOWSER (WROWSER) and will be visualized in it. In this case, different simulations are created, differentiated by random number seeds. seed(X) sets the integer starting value used in generating random numbers. If X was left empty, the generator took system time to generate the next random number, which caused undeterministic behavior and was undesirable. These random numbers are used to place UTs randomly in the whole scenario and to generate different number of UTs associated to a certain eNodeB in each simulation.

The predefined CreatorPlacerBuilderIndoorHotspot() is used to setup the IMT-Advanced InH Scenario. To speedup testing, only 2 UTs are set in the default configuration. But it can be increased to e.g. 20. The default eNodeB and UT creators are used to create these two kinds of nodes.

Downlink scheduling is Round Robin for all UTs. During each subframe, the full bandwidth should be allocated to one UT. In openWNS, this is implemented in the Exhaustive Round Robin scheduling strategy with any dynamic subchannel assignment (DSA) strategy, e.g. Linear First, Random or Fixed. This strategy is configured as the default down link strategy. Exhaustive means a UT is selected and will be scheduled in the subframe as long as it has data to transmit. In the next subframe, the next user will be selected. In a full buffer simulation, the users take turns to occupy whole frames.

Uplink scheduling is Frequency Division Multiple Access (FDMA), where each UT is assigned an equal share of resource blocks in each subframe. In openWNS, this strategy is implemented in DSA Driven Round Robin scheduling strategy with Fixed DSA strategy. This strategy is already configured as the default uplink strategy. At the beginning of each frame the number of associated UT is checked. The resources are then equally distributed. Each user will get exactly the same amount of resources in each frame, as long as the number of UT stays constant. This significantly reduces uplink SINR variance and channel estimation error.

More transmission power increases the received signal power and the perceived SINR. On the other hand, the more power a station emits, the more interference it will cause to other cells. The LTE module implements the open loop fractional pathless compensation power control behavior as specified by [11]. The formula used by UT to calculate its transmission power in uplink direction is $P_{TX} = P_0 + \alpha \cdot PL$, where both the base level P_0 and the fractional path loss compensation factor α are broadcasted by eNodeB. UT measures the path loss (PL) to the serving cell with the help of downlink reference signals and a proper time averaging function to determine the transmission power. $P_0 = -106dBm$ and $\alpha = 1.0$ is used in the InH Scenario simulation.

Two eNodeB are located in the scenario as indicated in Fig. 12. 20 UTs are placed randomly in the simulation. The constant rate traffic generator creates 1500 byte long Internet Protocol (IP) Service Data Units (SDUs). They are fed into UpperConvergence layer of the LTE system. The offered traffic of $15 \cdot 10^6$ bit/s is chosen. The segmenting queues within the resource allocation unit (scheduler) implement segmentation and concatenation to provide the exact amount of data fitting into the transmission block granted by the scheduler. Frequency and Time correlated Fading (FTFading) is also considered. For this InH scenario, the doppler spread is calculated according to the speed and center frequency, where speed is set to 3 km/h, center frequency is 3.4 GHz.

The WROWSER is the openWNS graphical user interface to browse simulation results in a fast and convenient way. In the following, all results are obtained in WROWSER.

Table II shows the number of associated UTs around eNodeB 1 at site S1 and eNodeB 2 at site S2, respecively. Different seed starting numbers are chosen, i.e. 2, 6, 10, 14 and 18. For example, for seed equals 10, exactly 7 UTs are in the coverage area of eNodeB 1, whereas 13 UTs are in that of eNodeB 2. Their sum corresponds to the total number of UTs in this scenario, which is exactly 20. The table also shows the outgoing throughput measured at the top of RLC layer of eNodeB 1 and eNodeB 2 for different simulations. The transmission direction is from eNodeB to UTs. These values correspond well to the number of associated users and the offered traffic provided by eNodeB.

TABLE II
SOME RESULTS IN INH

Seed	2	6	10	14	18
Number of UTs at S1	9	8	7	10	10
Number of UTs at S2	11	12	13	10	10
Outgoing Throughput at S1 [Mb/s]	130	120	110	150	150
Outgoing Throughput at S2 [Mb/s]	160	180	190	150	150

A Window probe FU is integrated in both, the eNodeB as well as the UT FUN at the top of rlc FU as indicated in Fig.11. It is used to cumulate the throughput in incoming and outgoing data flow in the unit of bit. *Aggregated throughput* is the outgoing throughput measured for only those PDUs that are finally received by the Window FU in the peer FUN. Thus, PDUs dropped in between are not accounted for as the aggregated throughput. Every predefined time interval, the throughput is recorded in the according probes. The throughputs are calculated as transmission units divided by the length of the time interval. Fig. 14 shows the aggregated outgoing throughput of UTs. Again, uplink traffic sent from UT to eNodeB is studied. The mean value of aggregated throughput is clearly less than that of outgoing throughput for each seed, which is plausible because of the definition of aggregated throughput. Fig. 15 illustrates the incoming throughput of UTs. For this case, the downlink traffic is observed. Data units are sent from eNodeB to UTs.

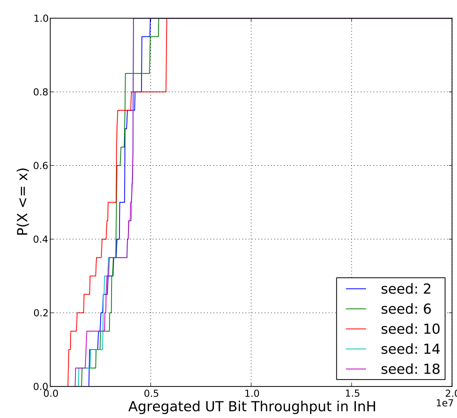

Fig. 14. CDF of Aggregated Throughput in bit/s in InH

The cumulative distribution function (CDF) of Signal to Interference plus Noise Ratio (SINR) for different seed starting number, i.e. 2, 6, 10, 14 and 18 is shown in Fig. 16. The best SINR is slightly above 50 dB, which implies that UT must be in a very good radio coverage area provided by the eNodeB, that it is associated with.

Besides the above mentioned distribution functions, the mean value of outgoing, incoming and aggregated bit throughput as well as mean received signal strength, interference and SINR for each different seed value are also available in WROWSER.

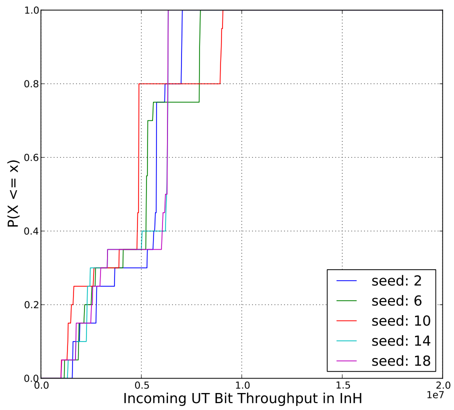

Fig. 15. CDF of Incoming Throughput in bit/s in InH

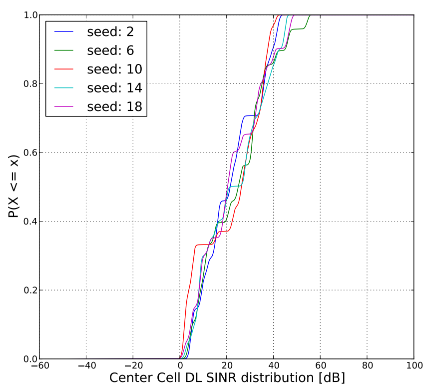

Fig. 16. CDF of SINR over the Whole Scenario in InH

B. Simulation Settings in UMa Scenario and Results

The predefined CreatorPlacerBuilderUrbanMacro () is used to setup the IMT-Advanced UMa Scenario. 10 UTs are configured in the simulation. The default BS and UT creators are used to create the nodes. Downlink scheduling, Uplink scheduling and UT's transmission power are configured as in InH scenario.

The simulated UMa scenario is illustrated in Fig. 13. A three-sector site contains three cells. One eNodeB handles the transmissions in such a three-sector site. The center site is surrounded by 6 sites. The 6 sites are surrounded by 12 further sites, causing more interference to the center one. In this simulation, only the direct 6 interferers are considered, that implies there are 7 sites and thus 21 cells under observation, which are numbered serially from 1 to 21. From the eNodeB point of view, one eNodeB is in the middle and 6 eNodeBs around the center eNodeB cause interferences to the center one. There are some new parameters defined in UMa scenario, e.g. number of circles and usage of sectorization. The center eNodeB is defined as circle 0. The surrounding 6 eNodeBs are circle 1. Sectorized antenna are used. In the simulation, the total number of eNodeBs is 7. 10 UTs are placed randomly and uniformly distributed over the whole service area. The antenna in eNodeB is 3 sectorized. The constant rate traffic generator creates 1500 byte long IP SDUs. The offered traffic is $15 \cdot 10^5$ bit/s. As in InH, FTFading is also considered in UMa scenario in LTE module. The doppler spread is calculated according to the speed and center frequency. Speed is set to 30 km/h, center frequency is 2 GHz for the UMa scenario.

TABLE III
SOME RESULTS IN UMA

Seed	2	6	10	14	18
Number of UTs in Cell 16	1	0	2	1	1
Number of UTs in Cell 21	0	0	0	1	3
Outgoing Throughput in Cell 16 [Mb/s]	1.5	0	3	1.5	1.5
Outgoing Throughput in Cell 21 [Mb/s]	0	0	0	1.5	4.5
Aggregated Throughput in Cell 16 [Mb/s]	1.5	0	3	1.5	1.5
Aggregated Throughput in Cell 21 [Mb/s]	0	0	0	1.5	4.5
Incoming Throughput in Cell 16 [Mb/s]	1.5	0	3	1.5	1.5
Incoming Throughput in Cell 21 [Mb/s]	0	0	0	1.5	4.5

A UT is said to be associated with a certain eNodeB, if it is served in one of the three cells, which belong to the site, that the eNodeB is responsible for. Table III shows the number of associated UTs in two example cells, i.e. cell 16 and 21 respecively. Different seed starting numbers are chosen, as in InH case. For example, for seed equals 2, one UT and no UTs is served in cell 16 and cell 21, respectively. For seed is equal to 18, one UT and three UTs are served in cell 16 and cell 21, respectively. The table shows the outgoing bit throughput in eNodeB, which is obtained in cell 16 and cell 21 served by a certain sector of two different eNodeBs, respectively. In this case, the downlink traffic is considered, where data units are transmitted from eNodeB to UTs. The throughput is measured at the top of rlc FU in the outgoing data flow of eNodeB. The aggregated bit throughput in eNodeB is also shown in the table. Again, downlink traffic is observed. But those data units that are not successfully delivered to UT FUN are not considered. At this moment, there is no difference at all between outgoing and aggregated throughput. This is because the number of UTs in the whole 21 cells, i.e. in the whole scenario is not large enough yet. The total traffic generated by eNodeBs to serve their associated UTs is still far from reaching the saturation point of the system capacity. Both mean throughput values correspond well to the number of UTs associated in each cell. For example, mean throughput is $15 \cdot 10^5$ bit/s in cell 16 and 0 in cell 21 for seed 2, whereas mean throughput is $15 \cdot 10^5$ bit/s in cell 16 and $45 \cdot 10^5$ bit/s in cell 21 for seed 18. The last two lines of the table show the mean incoming bit throughput in eNodeB contributed by cell 16 and in another eNodeB contributed by cell 21, respectively. In this case, the uplink traffic is studied. Data units are transmitted from UTs to eNodeBs. The results again correspond to the number of UTs served by cell 16 and 21 and the generated traffic rate by each UT.

Fig. 17 shows the CDF of SINR over the center site in UMa scenario. For some best case, the SINR value even reaches almost 80 dB, which is even higher than in the InH scenario. The reason for this could be the relative low number of UTs and the low offered traffic for each station in the current UMa simulation.

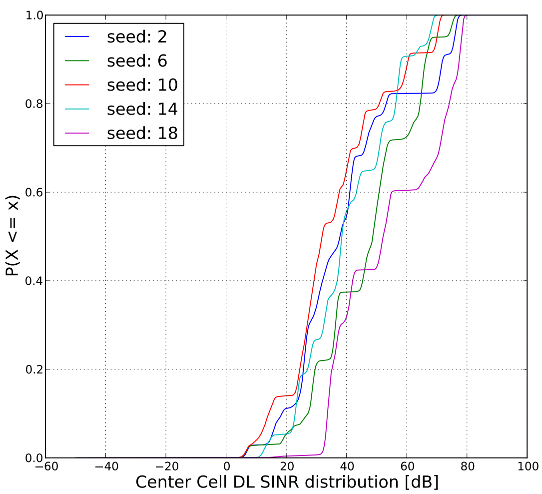

Fig. 17. CDF of SINR in the Center Site in UMa

The offered traffic is configured as $15 \cdot 10^5$ bit/s at each station and the number of UTs in UMa scenario is set to be 10. This implies, that the load of the system is relatively low and the system is far from being saturated. The next step of implementing the simulation model is to increase the offered traffic as well as the number of UTs served in the whole scenario to let the system reach a full buffer situation. The obtained results can be compared with those obtained in the analytical framework and furthermore the cell spectral efficiency as defined in [1] can be calculated and verified against each other.

VI. Conclusion and Outlook

In this paper, an SFG based analytical framework has been elaborated to analyze the system capacity and error ratio of different protocol layers at any location of an UT in 3GPP LTE system. In addition, two system level simulations have been presented, both in IMT-Advanced InH and UMa scenarios, using the calibrated LTE module of openWNS. The two scenarios are configured according to [2]. Model parameters like number of eNodeBs, UTs and offered traffic can be adjusted to evaluate the system performance, e.g. station throughput and SINR distribution functions. In the analytical model, a full buffer system is assumed. Capacity and error ratio of RLC layer are analyzed for the UMa scenario. The simulation model can calculate the station throughput under a given traffic load and a certain number of user terminals. Not only the InH but also the UMa scenario are simulated.

Some further work has to be performed related to the simulation model. The model must be able to support more UTs and higher offered traffic in the UMa scenario. It must be able to calculate the system capacity in the case of a full buffer system. Additional simulation experiments will have to be executed differentiated not only by random seed number, but also by increasing offered traffic. With such simulation experiments, the saturation point of the whole system can be figured out. Thus, the capacity of the simulated scenario can be obtained and then can be verified against the analytical model. The performance evaluation is currently obtained at the top of RLC layer. It will be interesting to further get results at the top of MAC layer as well as that of PHY layer, whose results can be further compared with those obtained by means of the analytical framework.

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