Analytical Validation of an IMT-Advanced Compliant LTE System Level Simulator

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***Abstract*—Multiple radio interface technologies (RITs) applied to be part of the family of fourth generation (4G) mobile radio networks within the IMT-Advanced process of the International Telecommunication Union (ITU). One promising technology for that is LTE-Advanced (LTE-A) standardized by the 3rd Generation Partnership Project (3GPP). Among other results, 3GPP has provided LTE-A system level simulation results for cell spectral efficiency and cell edge user spectral efficiency.**

The ITU has requested multiple independent evaluation groups to verify those results using their own simulators. For that simulator implementations must be verified for correct behaviour and correct assumptions. In this work we present a method to analytically derive system level simulator calibration results complying to 3GPP calibration assumptions. We also analyse the key factors and assumptions significant for overall system level performance.

I. Introduction

In March 2008 the International Telecommunication Union Radiocommunication Sector (ITU-R) has published a circular letter calling for proposals for next generation radio communication systems. Among others the 3rd Generation Partnership Project (3GPP) has proposed a set of radio interface technologies (SRIT), namely Long Term Evolution Advanced (LTE-A). Along with the description of the proposed system, a self-evaluation was submitted to the International Telecommunication Union (ITU).

Multiple external evaluation groups support the IMT-Advanced (IMT-A) process to verify the self-evaluation results. Besides others, system level simulation is an important method to evaluate the performance of candidate systems. To assure comparable results and agree on common assumptions, organisations involved in the evaluation process needed to verify their simulation models. The baseline reference configuration for LTE Release 8 calibration served as a starting point for the different organisations to calibrate against each other and against 3GPP. Multiple partners worked together in the European WINNER+ project to evaluate LTE performance. They have published their simulator calibration results in [1].

The channel model calibration results show that all used simulator implementations produce identical results and can therefore be considered calibrated and verified. The published system level calibration results show significant differences among the organisations. Especially the downlink throughput distribution results for the so called Indoor Hotspot scenario show high differences among organisations.

The channel model calibration can be considered successful since multiple independent bodies came to the same result using different simulators. Despite that the correct system level throughput distribution results remain unknown. It is not clear if the different results come from different assumptions or faulty simulator implementations. In the following we present an analytical model to prove the correct implementation of the Open Source Wireless Network Simulator (openWNS) used to evaluate Long Term Evolution (LTE) performance within the WINNER+ project. The model proves the correct implementation of the simulator but does not allow any conclusions regarding the simulation model assumptions.

The remainder of this work is organised as followed: In the remainder of this Section we describe the IMT-A evaluation methodology for cell spectral efficiency (CSE) and cell edge user spectral efficiency. In Section II we introduce the analytical model yielding the same results as the system level calibration, which are presented in Section III. We conclude the work in Section IV and give an outlook on possible future extensions.

A. *IMT-Advanced Evaluation Methodology*

The IMT-A Evaluation Methodology document M.2135 [2] defines four test environments in which candidate radio interface technologys (RITs) have to prove their performance. Defined methods for performance evaluation are system and link level simulation, mathematical analysis, and inspection. The last one means checking the specifications of the RIT for compliance with IMT-A requirements. The cell spectral efficiency, cell edge user spectral efficiency and Voice over IP (VoIP) capacity are evaluated by system level simulation.

The test environments for evaluation are *Indoor*, *Microcellular*, *Base coverage urban*, and *High speed*. Each environment has a specific geometric deployment scenario namely Indoor Hotspot (InH), Urban Micro (UMi), Urban Macro (UMa), and Rural Macro (RMa), defined by the cell size and Inter-site distance (ISD) for the last three. The InH scenario is formed by a rectangular floor spanning 120 m by 50 m with two Base Station (BS) sites as shown in Figure 1. The BSs in the InH scenario are equipped with omnidirectional antennas, while the cellular scenarios define three sector BS sites. For each scenario the carrier frequency, transmission bandwidth, maximum transmission power, transceiver height, and number of antenna elements is defined. The channel model consists of a large- and a small scale fading component with individual parameters for each scenario.

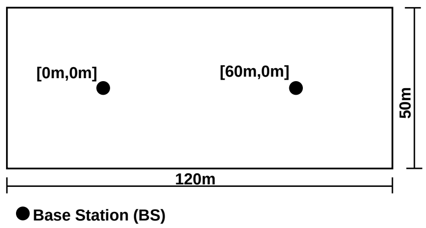

Fig. 1. IMT-Advanced Indoor Hotspot scenario.

The large scale channel model defines a fixed, distance dependent, path-loss and additionally a log-normally distributed shadowing loss with standard deviation σ_c. Multiple simulation runs, each with different uniformly distributed random User Terminal (UT) positions, are performed to obtain results. For each run the path-loss is fixed due to the fixed UT positions. The realization of the random shadow loss is drawn once for each link and remains constant for the entire simulation run. The path-loss is calculated using the formula $PL = \beta_c + \gamma_c \log_{10} d$, where d is the distance between the communicating nodes. The index c indicates that the standard deviation σ_c, the fixed offset β_c, and the slope γ_c depend on the channel conditions. The channel conditions can be either line-of-sight (LoS) or non line-of-sight (NLoS). For each simulation run the channel conditions for each link are determined randomly following a distance dependent distribution.

B. Related Work

Results for upper and lower bound CSE for cellular scenarios with reuse distance equal or greater two are presented in [3]. The authors of [4] present a model to obtain results for reuse-1 scenarios without shadowing and also provide lower and upper bound approximations. In [5] we present a method to derive the uplink capacity in scenarios with assumptions similar to the IMT-A evaluation methodology under reuse-1 and Fractional Frequency Reuse (FFR). The authors of [6] provide CSE results for cellular IMT-A scenarios with relays but do not include random shadowing in their model.

The system level simulator openWNS validated in this work has been used to produce LTE-A performance results in IMT-A compliant scenarios [ETT Paper dbn?].

II. Signal to Interference and Noise Ratio (SINR) Distribution Calculation

To derive the overall downlink (DL) SINR distribution of the InH scenario we first derive it for a single UT at position $[x, y]$. We choose the position of the left BS as the origin of the coordinate system. In this case the distance to the left BS is $d_L = \sqrt{x^2 + y^2}$ and $d_R = \sqrt{(x-60)^2 + y^2}$ the distance to the right one. Using equation (1) the LoS probability for the links to each BS can be calculated. For now we assume the UT has a LoS connection to both BSs. The probability for this is $P(c = LoS|d_L)P(c = LoS|d_R)$, since the channel conditions on the links are stochastically independent.

$$P(c = LoS|d) = \begin{cases} 1, & d \leq 18 \\ exp(-\frac{d-18}{27}), & 18 < d \leq 37 \\ 0.5, & d > 37 \end{cases} \quad (1)$$

The path-loss to each BS is then normally distributed with mean value $\mu_{LoS}(d) = \beta_{LoS} + \gamma_{LoS} \log_{10}(d)$ since the random shadowing component of the path-loss is normally distributed. The probability density functions (PDFs) are $p(PL_L) = N(\mu_{LoS}(d_L), \sigma_{LoS})$ and $p(PL_R) = N(\mu_{LoS}(d_R), \sigma_{LoS})$ for the path-loss to the left and right BS respectively. The results for a UT located at $[20m; 15m]$ are shown in Figure 2. The UT will choose the BS it experiences the lower path-loss to as the serving BS. The probability to be associated to the left BS equals the probability $P(a = L) = P(PL_R > PL_L)$. This equals the probability for the path-loss difference to be greater zero $P(a = L) = P(PL_R - PL_L > 0)$. The distribution of the difference of the two normally distributed path-losses is:

$$p(PL_R - PL_L) = N(\mu_{LoS}(d_R) - \mu_{LoS}(d_L), \sqrt{\sigma^2_{LoS} + \sigma^2_{LoS}}) \quad (2)$$

.

The resulting probability can be calculated using Equation (3).

$$P(a = L) = P(PL_R - PL_L > 0) = \\ 1 - \frac{1}{2}\,\text{erf}\left(\frac{\mu_{LoS}(d_L) - \mu_{LoS}(d_R)}{\sqrt{2(\sigma^2_{LoS} + \sigma^2_{LoS})}}\right) \quad (3)$$

Since both BSs transmit with the same power, the resulting SINR in dB can be calculated as $PL_R - PL_L$. The distribution of the path-loss differences $p(PL_R - PL_L)$ is also normally distributed. Taking into account which BS is serving, the SINR distribution of a UT served by the left BS with LoS channel conditions on both, the serving and the interfering link, is:

$$p(SINR|a = L) = \frac{p(PL_R - PL_L)\mathbf{1}_{\{SINR \geq 0\}}}{P(a = L)}. \quad (4)$$

The indicator function $\mathbf{1}_{\{SINR \geq 0\}}$ assures that only SINR values greater zero are possible. Values below zero are not possible since in this case the right BS would be serving the UT. The resulting PDF is shown in Figure 2.

The SINR distribution for the given position and channel condition can be mapped to a date rate distribution. For that an SINR to Modulation and Coding Scheme (MCS) mapping has to be done. A subset of 13 MCSs defined by the LTE standard are used. The mapping is showed in Figure 3 for a channel bandwidth 20 MHz and further described in [7]. The MCSs have been used by some organisations within the WINNER+ project to create system level simulation results. Three out of 14 symbols are used for the Downlink Control Channel (DLCCH) according to [8]. Overhead introduced by the Broadcast Control Channel (BCH) is neglected since it is only transmitted every tenth frame. The rate is further reduced

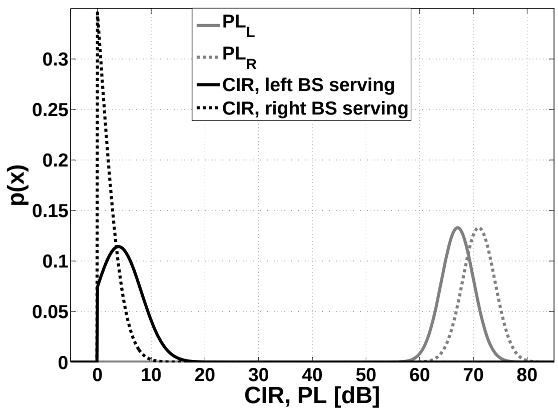

Fig. 2. Path-loss and SINR distribution for an UT at position [20 m; 15 m] with LoS channel conditions on both links.

by 8 bit fixed Radio Link Control (RLC) header and 32 bit Media Access Control (MAC) header in each frame. The code rate has been reduced to model 8 symbols per Resource Block (RB) used as reference symbols not available for user data traffic.

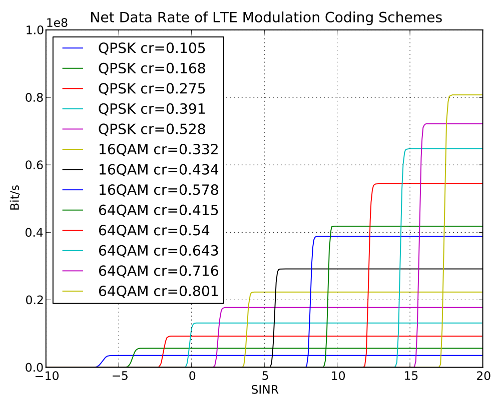

Fig. 3. Mapping of SINR to data rate at 20 MHz channel bandwidth used for system level simulation.

The results are used to obtain switching points between available MCSs guaranteeing a maximum Packet Error Rate (PER) of 1 %. The minimum SINR for an MCSs of data rate r_i is denoted $SINR_{r_i Min}$. With this formula (4) can be used to obtain the probability $P(r_i|x, y, a, c_L, c_R) = P(SINR_{r_i Min} < SINR < SINR_{r_{(i+1)} Min}$ for each MCS.

This MCS distribution is only valid for an UT served by the left BS with LoS channel condition on the links to both BSs. If the UT is served by the right BS, the mean values $\mu_{LoS}(d_L)$ and $\mu_{LoS}(d_R)$ in formula (2) are just switched to obtain $P(a = R)$ and $p(PL_L - PL_R)$. This result is also shown in Figure 2. Besides LoS channel conditions, the UT could also have an NLoS link to either one or both BSs. In this case the according mean values and variances of the path-loss distributions have to be changed.

In total there are eight possible combinations: Each link has two possible channel conditions and either of the two BSs can be serving the UT. The probability for each combination is given by Equation (5).

$$P(a = A, c_L = C_L, c_R = C_R) = \\ P(a = A)P(c_L = C_L|d_L)P(c_R = C_R|d_R) \tag{5}$$

The overall data rate distribution for a given position $[x; y]$ is then the weighted superposition of the probability for each conditional rate distribution:

$$P(r_i|x, y) = \\ \sum_{\forall a, c_L, c_R} P(a, c_L, c_R)P(r_i|x, y, a, c_L, c_R) \tag{6}$$

Twenty user terminals are placed randomly in the scenario for system level simulation. Each terminal associates to the BS serving it with highest SINR. Since the scenario is symmetric, the probability to be served by either one of the BSs equals 0.5. Repeating the experiment for all 20 UTs results in the number of associated UTs a to be Binomially distributed $B(a|n, p)$ with $n = 20$ trials and $p = 0.5$ success probability.

Each UT receives the same amount of resources according to 3GPP LTE calibration assumptions [8]. The achievable throughput therefore depends on how many UTs are served by a BS. It has to be divided by the number of associated UTs a. Each MCS with rate r_i results in a defined throughput. If an UT has to share the channel with a other stations it only reaches the throughput r_i/a. The probability to achieve a throughput r_i/a is then $P(r_i/a|x, y) = B(a|20, 0.5)P(r_i|x, y)$.

$$P(r_i/a) = \iint_A \frac{P(r_i/a|x, y)}{A} \tag{7}$$

$$\eta = \iint_A \frac{P(r_i|x, y)}{A} \tag{8}$$

For the overall throughput distribution the results need to be integrated over the entire scenario and normalised to the area $A = 50 \cdot 120$ m^2 as done in formula (7). As far as we know there is no closed form solution for the integral. For that we numerically sum up the data rate distributions at each position and normalise the result to the number of sampling points.

The CSE η does not depend on the number of associated stations a since the throughput of all stations is summed up. It is obtained by numerically solving (8).

III. SINR Results

The channel model, especially the wideband SINR distribution, has significant impact on simulation results. Formula (4) for all combinations of channel conditions and serving BS, integrated over the scenario area and normalised, results in the downlink SINR distribution. The result is shown in Figure 4 along with results form the openWNS simulator. The BSs of the simulator permanently transmits and the UTs measure the received signal assuming the higher received signal is the one from the serving BS and the other BS is interfering.

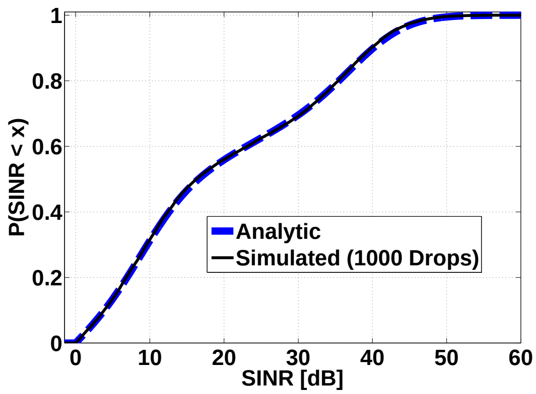

Fig. 4. SINR distribution for the whole scenario area.

The analytic results match the simulator results. This way the implemented channel model has been verified. The results match the calibration results presented in [1].

Next, the results of the LTE Release 8 calibration are obtained and compared to the analytic model. According to [8] the nodes are served by a RoundRobin scheduling strategy assigning each station the full bandwidth (100 RBs) in each frame. For this results small-scale channel fading is not applied. Figure 5 shows the distribution of the used MCSs. Simulation results for 50 and 500 drops together with the 95% confidence interval are shown. The analytic model used a step width of 1 m to numerically integrate over the area.

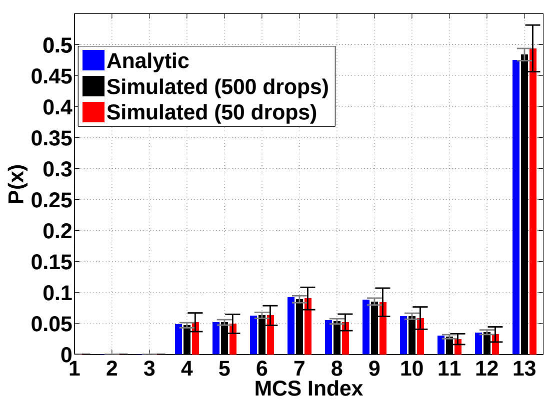

Fig. 5. Probability for each MCS.

The analytic results match the simulation results. Increasing the number of drops does not improve the results significantly.

Figure 6 shows the distribution of the number of associated nodes again for 50 and 500 simulation drops. Results are compared to the Bernoulli distribution used in the analytic model. It is now visible that simulation result confidence is significantly improved by increasing the number of drops.

The results of the user throughput distribution are shown in Figure 7. With 50 drops small differences between the analytic and simulation results around 5 Mbps to 6 Mbps are visible.

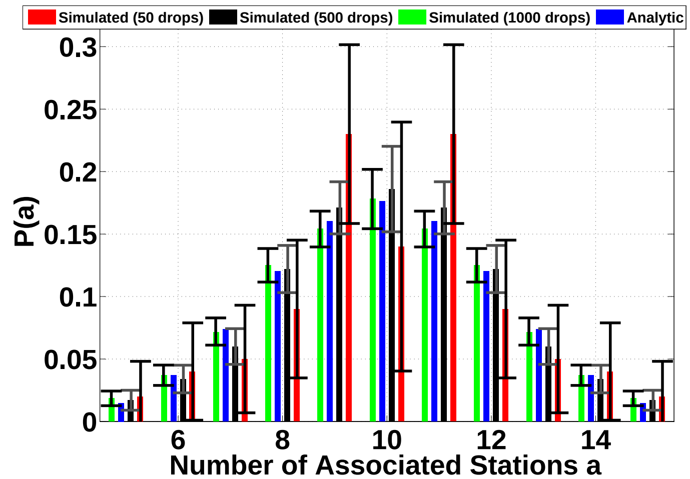

Fig. 6. Distribution of the number of associated users per system.

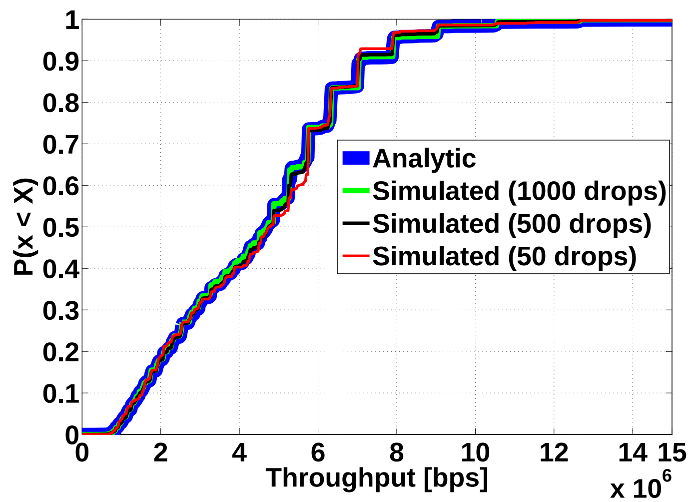

Fig. 7. Downlink throughput distribution.

Small differences to the analytic results for this throughput range are also visible for 500 drops. With 1000 drops no significant difference between simulated and analytic results are visible.

The CSE η is found to be 2.269 Bit/s/Hz/Cell using formula (8). This is very close to the simulator result 2.265 Bit/s/Hz/Cell for 1000 drops. The cell edge user spectral efficiency defined as the 5-percentile of the throughput distribution is 0.057 Bit/s/Hz for both, the analytic model and the simulation for 1000 drops. Figure 8 shows how the relative error of the CSE and cell edge user spectral efficiency decreases as the number of drops is increased. Less than 30 drops are required to assure an error below 1 % for the CSE. More than 80 drops are needed to assure no more than approximately 1 % deviation for the cell edge user spectral efficiency.

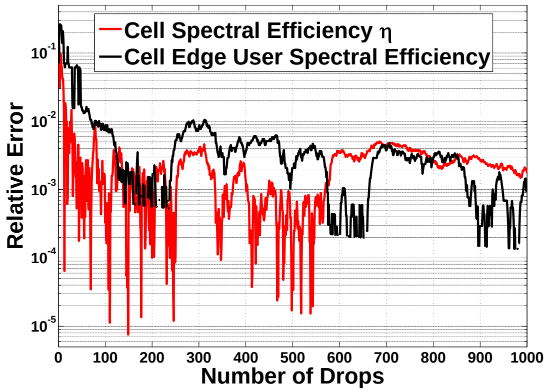

Fig. 8. Relative Error of Simulation Result Compared to Analytic Result.

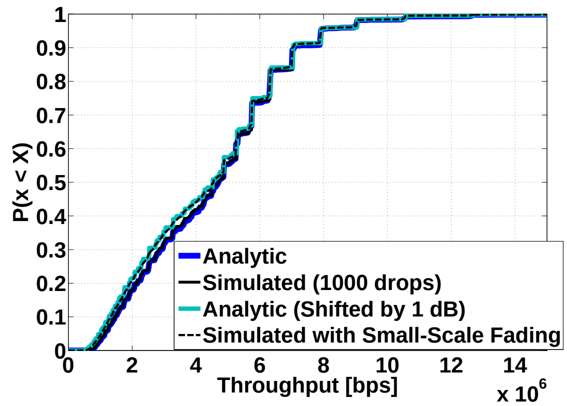

Fig. 9. Results with Active Small-Scale Fading.

A. Performance and Future Extensions

The simulation time was set to two seconds. Results are measured during the last simulation second. A single simulation takes 7 minutes real time but it could be speed up by decreasing the settling time and the time used for measuring. On the same platform analytic results are obtained after 45 seconds at 1 m resolution and 70 minutes with 0.1 m resolution. The higher resolution does not influence the results significantly. For symmetry reasons it is enough to integrate over one quarter of the scenario area.

The model needs to be extended to be applicable to cellular scenarios. Multiple interferers are then present resulting in interference power to have the distribution of the sum of lognormally distributed random variables, to which no closed form solution is known. Numerical methods or approximations as presented in [9], [10] need to be used for that. Antenna gains can be easily included in this model causing an additional factor in the fixed path-loss component. For the InH scenario with two BSs eight combinations for channel conditions and serving BS exist. In general there are $b2^b$ combinations if there are b BSs since each of the b links can have LoS or NLoS channel conditions and each of the BSs can be serving BS.

The IMT-A small-scale fading model has not been included in this work. The authors of [11] show that the Shannon capacity of a Rayleigh fading channel can be calculated by introducing a constant SINR shift. Figure 9 shows simulator results including small-scale fading. We were able to closely match the results by shifting the SINR distribution in Formula (4) by 1 dB. Small-scale fading has only little impact since data is transmitted on all 100 RBs causing the effective SINR of a transmission to be calculated as the average over many channel realisations. Due to the low speed of 3 km/h in the InH scenario channel coherence time is long enough to assure accurate channel state information available for scheduling and a negligible error probability due to channel estimation errors.

IV. Summary, Conclusion, and Outlook

An analytic model to verify system level calibration results for spectral efficiency and cell edge user spectral efficiency in the IMT-Advanced Indoor Hotspot scenario has been developed. It verifies the correct implementation of the openWNS simulator used for LTE performance evaluation.

We have found that intermediate results like the MCS distribution and especially the number of associated UTs show significant differences to the analytical model if the simulation experiment is repeated only few times. Still the key performance indicator results for cell spectral efficiency (CSE) and cell edge user spectral efficiency show high confidence after only a few (less than 100) simulation drops.

The model can be easily extended to gain results for more than two cells and to include antenna patterns. Power control and other scheduling strategies apart from RoundRobin can be included to gain analytic results for possible radio resource assignment optimisations.

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