Verification of the Vienna 5G Link and System Level Simulators and Their Interaction

Stefan Pratschner*†, Martin Klaus Müller*†, Fjolla Ademaj*†, Armand Nabavi†, Bashar Tahir*†,
Stefan Schwarz*† and Markus Rupp†
*Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion
†Institute of Telecommunications, TU Wien, Austria
Email: stefan.pratschner@tuwien.ac.at

***Abstract*—Numerical simulation of wireless communications systems is an important means within the process of development and evolution of mobile communications specifications. We offer a software suite to the academic society for free under an academic use license that enables the community to perform simulations of relevant scenarios for 5G and beyond in a reproducible manner. To cover a variety of potential scenarios for future mobile communications systems, we offer the Vienna 5G Link Level (LL) Simulator and the Vienna 5G System Level (SL) Simulator. In this contribution, we perform a verification of our LL and SL simulators which allows us to claim simulation results to be valid. As the Vienna 5G SL Simulator relies on link performance simulation results carried out with the Vienna 5G LL Simulator, we further consider their interaction in the context of verification.**

I. INTRODUCTION

Requirements for future mobile communications standards are steadily increasing. Along the demand for high data rates in the context of enhanced mobile broadband, other system aspects, such as massive machine-type communication or ultra-reliable and low-latency communication, increase the variety and complexity of the radio access network (RAN) specification [1]–[3]. At the same time, mobile communications networks for 5G and beyond are becoming larger and more heterogeneous, further pushing the overall system complexity. As state of the art wireless communications systems support a large variety of use cases and are therefore implicitly complex, more and more effort is required for analysis, performance comparison and further development of such systems. While analytic results, for example for system performance in terms of throughput or latency, offer a high level of insight and reveal system parameter dependencies, obtaining them is often not tractable for aforementioned communications systems. In these cases, numerical simulation is an important and widely used tool for analysis of state of the art communications standards and further development towards novel systems.

To this extent, we offer the Vienna Cellular Communications Simulators (VCCS) software suite for free to fellow researchers under an academic use license, available at [4]. Currently, it contains the Vienna Long Term Evolution-Advanced (LTE-A) Link Level (LL) Simulators [5] and Vienna System Level (SL) Simulator [6], as well as the Vienna 5G LL Simulator [7] and the Vienna 5G SL Simulator [8]. While the development of the Vienna LTE-A Simulators started already in 2009, the Vienna 5G Simulators are very recent members within the VCCS suite. The success of these simulators, counting more than 50 000 downloads so far, underlines the demand and popularity of numerical simulation tools.

Simulation of a RAN or a heterogeneous wireless network offers means for analysis alternatively to analytic approaches. However, simulation without any comparison or verification renders obtained results meaningless. While there exist different approaches for this, such as comparison to measurements, analytical results, or other simulation tools, the verification itself is a necessity.

The Vienna 5G SL Simulator considers wireless networks on a large scale, offering the possibility to simulate scenarios that include hundreds of nodes. To keep the computational complexity at a feasible level, link abstraction is performed, that is, link quality models (LQMs) and link performance model (LPM) are employed. As the Vienna 5G LL Simulator aims to simulate the RAN in terms of a single link or wireless networks with only a few nodes, but with a very high level of detail, it serves to generate calibration data for the LQM and LPM. In this way, results from LL simulations are exploited within the SL simulator, thus making verification of these simulation tools a coupled task.

Contribution: In this work, we consider the process of verification of the Vienna 5G Simulators to ensure significance and meaningfulness for any sort of generated simulation result. As the Vienna 5G SL Simulator itself, relies on link performance data obtained with the Vienna 5G LL Simulator, their interaction is of high importance for their operation as well as for their verification. To this extent, we describe the joined operation of both simulators in the context of verification.

II. THE VIENNA 5G LL SIMULATOR

A. Introduction to the Simulator

During the development of 5G new radio (NR), numerous candidate physical layer (PHY) schemes were considered as possible improvement to the 3rd Generation Partnership Project (3GPP) LTE-A standard [9], [10]. While the diverse development of RAN methods is desirable from a scientific point of view, benchmarking a variety of proposed schemes is a complex task due to the manifold of performance metrics, such as latency, robustness or spectral efficiency. There exist various free simulation tools that allow detailed analysis of communication links and PHY methods, such as [11]–[13]. However, neither of these platforms support LL simulation of modern mobile communications networks, that is, 5G and beyond, with multiple communication links between base stations (BSs) and users.

The Vienna 5G LL Simulator is, as already revealed by the name, a LL simulator. It therefore avoids abstract mathematical models, such as a model for block errors, but is rather a straightforward implementation of a wireless transmission in a very high grade of detail. Specifically this means, that the process of signal generation, transmission over a wireless channel and reception is implemented in base band, up to the granularity of signal samples. While this approach relies on basic and well established models for signal propagation, the high level of detail within the simulation leads to a high computational complexity per simulated communication link. Therefore, LL simulation focuses on small wireless communications networks with few nodes, but enables to investigate and analyze effects, such as inter-user interference (IUI) due to non-orthogonal waveforms, very accurately.

Further, LL simulation does not define any network geometry such as cell size or user position, and therefore does not require path loss or shadow fading models. In contrast to SL simulations, a user's signal to noise ratio (SNR) is an input parameter to the simulation, rather than a simulation result and is directly controlled via the transmit power, path loss and noise power level. Typical simulation results are given in terms of throughput, bit error ratio or frame error ratio (FER).

B. Link Level Simulator Features

With the Vienna 5G LL Simulator we offer a versatile and flexible simulation platform to the wireless communications community, enhancing reproducibility in research. Its versatility lies in the wide range of allowed input parameter sets, such that basically any multi carrier system may be parametrized. As the modulation scheme may also be different among BSs, this allows investigation of co-existence of wireless communications standards, limited only by the frame duration of the per-frame processing of the simulator. To enhance usability of our simulator and enable parameter sets according to a specific communication standard, such as LTE-A or 5G NR, we offer pre-defined simulation scenarios within the simulator download package. Alternatively, the flexible way of object oriented implementation allows a re-use of offered features, such as channel coding or signal modulation, in a different, user defined, context. Further, the modular object-based structure serves as a future proof design, as new PHY methods may be added in a straightforward way.

Currently, the Vienna 5G LL Simulator offers various waveforms (cyclic prefix orthogonal frequency division multiplexing (OFDM), filtered OFDM (f-OFDM), weighted overlap and add, universal filtered multi carrier and filter-bank multi carrier (FBMC)), channel coding schemes (turbo coding, convolutional coding, polar coding and low-density parity-check (LDPC) coding [14]), multiple-input multiple-output transmission modes (transmit diversity, receive diversity and spatial multiplexing in terms of open loop spatial multiplexing and closed loop spatial multiplexing) and non-orthogonal multiple access transmissions. Supported channel models are power delay profile (PDP) based, for example the 3GPP tapped delay line models, while time selectivity is realized via a sum of sinusoids approach from [15], [16] and spatial correlation is implemented via a Kronecker model according to [17].

TABLE I

SIMULATION PARAMETERS FOR THE COMPARISON BETWEEN THE VIENNA LTE-A LL SIMULATOR AND THE VIENNA 5G LL SIMULATOR.

Parameter	Value
number of frames (TTI)	5000
waveform	OFDM
CP length	4.76 µs
subcarrier spacing	15 kHz
number of subcarriers	72
bandwidth	1.4 MHz
channel coding	Turbo coding
channel model	AWGN

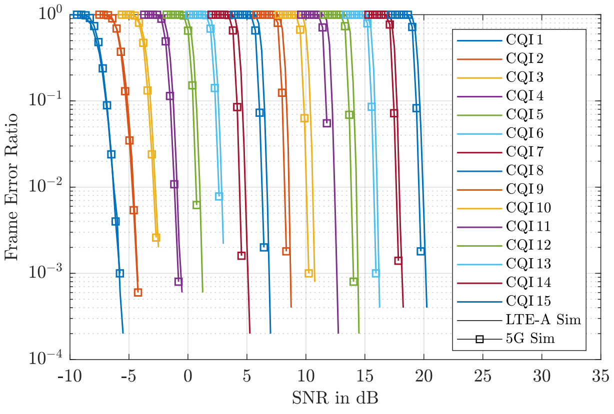
C. Verification of the Simulator

Verification is a necessity for any kind of numerical simulation tool, in order to render produced results meaningful for the intended real world application. In our special case, of a LL simulator for a wireless communications networks, it needs to be ensured that the obtained results are representative on average, for the modeled communications scenario. The LL Simulator does not rely on abstraction of propagation mechanisms or parts of the signal processing chain. The verification might be achieved in two ways: Results for a well defined scenario are either compared to measurements of such a scenario, or they are compared against results obtained with another, already verified, simulation tool.

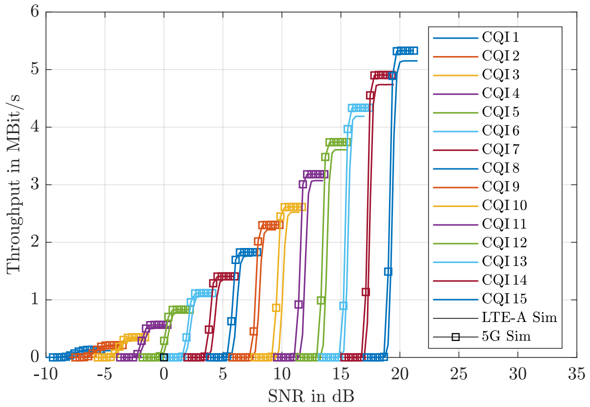
For verification of the Vienna 5G LL Simulator we choose the latter approach and compare simulation results obtained with the 5G LL simulator to results from the LTE-A LL simulator, re-assembling the same scenario. The Vienna LTE-A LL Simulator was verified by measurements [18] and is a well developed simulation tool. As it was widely used by the mobile communications research community, many user reports via our online forum [4] and further development of the tool through our research group make the LTE-A LL simulator a mature and reliable tool.

An exemplary comparison between the Vienna LTE-A LL Simulator and the Vienna 5G LL Simulator itself is carried out with the simulation parameters as summarized in Tab. I. A high number of transmissions is carried out over an additive white Gaussian noise (AWGN) channel for each channel quality indicator (CQI) value from 1 to 15 as defined in [19]. Results from both simulators in terms of FER are shown in Fig. 1a while results in terms of throughput are shown in Fig. 1b.

The curves for both simulators show a good match in general, however, there is a small deviation in the throughput result, both, with respect to SNR as well as with respect to the saturation value of each CQI value. The deviation in terms of SNR, meaning a shift of curves in the direction of the



(a) Simulation results in terms of FER.



(b) Simulation results in terms of throughput.

Fig. 1. Simulation results of a comparison between the Vienna LTE-A Downlink LL simulator and the Vienna 5G LL Simulator.

abscissa, is explainable by a more efficient channel decoding algorithm implemented in the Vienna 5G LL Simulator. Therefore, a certain value of throughput is reached already at an approximately 1 dB lower SNR compared to the LTE-A simulator. The deviation in terms of saturation throughput per CQI value originates in the implementation of the rate matching algorithm within the turbo channel coder, which was improved in the Vienna 5G LL Simulator. Therefore, the throughput saturation values perfectly coincide with the defined CQI value spectral efficiency, when pilot overhead is taken into account.

Results of the previously described simulation not only serve as a comparison between LL simulators, they also provide calibration values for effective signal to interference and noise ratio (SINR) mappings within the feedback calculation [20]. Furthermore, the simulation results shown in Fig. 1 also establish the connection from LL to SL simulation, via the LPM and the LQM as further explained in Section III. Please note that, although simulations are carried out in the context of LTE-A here, any parameterizable multi carrier system with any supported waveform and channel coding scheme is applicable to produce a similar set of simulation results. Thereby, it is possible to set up LPMs and LQMs for arbitrary multi carrier systems, which are then in turn also supported by the Vienna 5G SL Simulator.

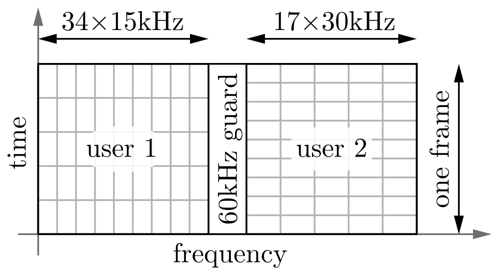


Fig. 2. Resource allocation for the exemplary simulation scenario.

D. *Exemplary Simulation Scenario*

In order to demonstrate distinct features of the Vienna 5G LL Simulator, such as various waveforms or the capability to simulate multiple links, we describe an exemplary simulation scenario in this section. While we include only a single scenario in this contribution, there are several representative scenarios available together with the simulator, as described in [7] as well as in the simulator's documentation [4].

We assume two users in an uplink transmission, which are scheduled next to each other in the frequency domain, as shown in Fig. 2. While the waveform is the same for both users, user 1 employs a subcarrier spacing of 15 kHz and user 2 employs a subcarrier spacing of 30 kHz. This represents a use case in terms of flexible numerology within 5G NR [22]. Therefore, unlike an LTE-A system, where users are automatically orthogonal due to the OFDM modulation, the users are non-orthogonal in this scenario and suffer from IUI. As our LL simulator allows simulation of multiple communication links, it enables analysis of interference and its effects between the two users. To further investigate the impact of the choice of waveform on the out of band (OOB) emissions, we compare OFDM, f-OFDM and FBMC in this scenario. Simulation parameters are summarized in Tab. II.

To investigate the impact of the IUI on the system performance including channel coding, we show the coded throughput of user 1 in Fig. 3. These results are plotted over user 2's transmit power, which is considered as interference for user 1

TABLE II
SIMULATION PARAMETERS FOR THE EXEMPLARY SIMULATION SCENARIO.

Parameter	Value		
waveform	OFDM	f-OFDM	FBMC
filter type	-	Hanning	PHYDYAS-OQAM [21]
filter length	-	7.14 µs	-
CP length	4.76 µs	4.76 µs	-
subcarrier spacing	user 1: 15 kHz, user 2: 30 kHz		
guard band	2 × 15 kHz + 1 × 30 kHz = 60 kHz		
bandwidth per user	34 × 15 kHz = 17 × 30 kHz = 0.51 MHz		
modulation/coding	64 QAM/LDPC, r = 0.65 (CQI 12)		
channel model	block fading Pedestrian A		

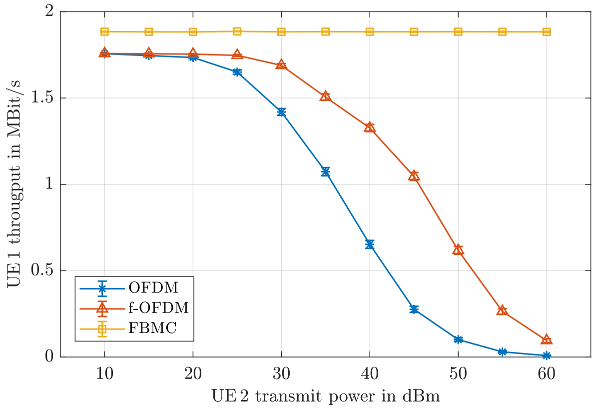


Fig. 3. Simulation results of the example scenario. Throughput of user 1 is plotted over of transmit power of user 2. The transmit power of user 1 is 30 dBm. Values are represented by their mean together with their 95% confidence interval obtained by bootstrapping.

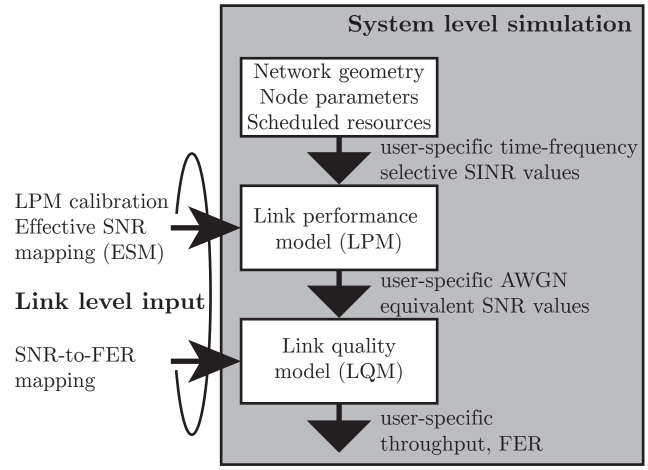


Fig. 4. Illustration of the interaction between the LL and the SL simulators.

in this scenario. While this transmit power is swept to very high absolute values in this simulation, please note, that this value has to be seen relative to user 1's transmit power, which is 30 dBm. We observe, that user 1's throughput decreases with increasing interference power for OFDM as well as for f-OFDM. However, the effect of IUI is smaller if both users employ f-OFDM compared to OFDM. The filtering reduces the OOB emissions in the f-OFDM case such that the guard band between the two users leads to a reduced amount of interference. For the FBMC case, we observe that the guard band in frequency domain between the users is sufficiently large, such that the extremely sharp spectral confinement of FBMC prevents all effects of IUI.

III. CONNECTING LINK LEVEL AND SYSTEM LEVEL

To enable investigation of large wireless communications networks, consisting of hundreds of nodes, in terms of SL simulations, simplifications of the individual communication links are required for feasibility reasons. As already mentioned, this is achieved via the so called LQM and LPM [8], [23]. The connection between the two simulators through these models is illustrated in Fig. 4. The LQM outputs a communication link's quality, including channel decoding as well as equalization, in terms of a post equalization SINR. Within the LPM, these SINR values per allocated subcarrier are mapped to a single, effective SINR value, employing mutual information effective SINR mapping (MIESM) [24]–[27]. The LPM then applies a mapping from the effective SINR value to the FER and throughput via the simulated AWGN reference curves obtained by LL simulation. An important assumption here is that the interference is approximately distributed according to a Gauss distribution. Thus, the interference can simply be treated as additional noise.

This modeling approach is not only beneficial in terms of reduction of computational complexity for SL simulation, it is also universal in the sense that the described mapping data may be obtained for almost any multi carrier system by LL simulation. This renders the implementation of the Vienna 5G LL Simulator and the Vienna 5G SL Simulator future proof, since novel PHY methods can be included in a straightforward manner in the LL simulator and then further exploited in the SL simulator through the described modeling procedure.

The previously discussed verification of the Vienna 5G LL Simulator renders the simulation results shown in Fig. 1 reliable. The trustworthiness of these results is also a necessity for the Vienna 5G SL Simulator simulator, since the utilized abstraction method in the LPM and the LQM rely upon them.

IV. THE VIENNA 5G SL SIMULATOR

A. Introduction to the Simulator

The task of a SL simulator is to simulate large scale networks with potentially several hundred or more network nodes. Since the sheer size of networks forbids to simulate the wireless transmission in full detail in terms of computational complexity, the efficient abstraction methods as described in Section III inevitably have to be employed. In the context of emerging 5G networks, SL simulators do not only have to handle a large number of network nodes, but also have to be able to distinguish among a multitude of BS and user types. This is required in order to simulate heterogeneous multi-tier networks as well as a mix of users with different requirements and link-conditions.

While there exists a significant amount of tools to perform SL simulations in an LTE-A context [28], [29], the number of available 5G SL simulators is rather small. They are either add-ons to existing LTE-A SL simulators [30], [31], are limited in the number of network nodes [12], or are not available to others [32]. With the Vienna 5G SL Simulator, we provide a novel tool in order to fill the existing gap for 5G SL simulators and also make it freely available under an academic use license.

We designed our simulator according to the requirements of 5G networks. One of the key demands for 5G simulators, is a high flexibility of the general simulator structure as well as scalability in terms of additional functionality (cf. [33]).

Therefore, the simulator is implemented in a modular fashion, utilizing object oriented programming and combining related functions in packages. This way, existing functions can be adapted or new functions can be added conveniently, without the need to make changes at several parts of the code. Thanks to this abstract structure, it is possible to compare different scenarios with respect to network elements and network geometry, propagation models or media access control (MAC) layer functionality.

B. System Level Simulator Features

As already stated above, an arbitrary amount of BS and user types can be defined. This means that the individual parameters per network element, such as number of antennas, antenna height or transmit power, can be adjusted freely. Additionally, regarding the number and placement of the network elements, several options are implemented (but new functions can be added, as long as they follow the required output format). For BSs, the classical hex-grid is an available placement option, as well as random number and placement according to a Poisson point process (PPP), next to other predefined placement options. For users, also several options are available, e.g., clustered placement, but also placement on streets or in buildings. These street and building objects are also modeled explicitly in our simulator and are used not only for placement, but also for identifying link-conditions, such as line of sight (LOS)/non line of sight or indoor/outdoor.

There are several different classes of propagation models included that all have an influence on the received power of the individual link. We provide path loss and channel models, an implementation of correlated shadow fading [34], several antenna patterns and blockage objects that influence the link either through changing the link condition or by adding an arbitrary penetration loss per object. A specialty of our simulator is the link-dependent choice of the path loss model based on the condition of the link. This is exemplified in Section IV-D. For all types of propagation models, new functions can be defined as required, as long as they fit the necessary input/output format.

The MAC layer is represented by the scheduler function in combination with the feedback calculation. Based on the link quality, determined through the received power of desired and interfering nodes, and dependent on the network geometry and propagation models, the feedback function calculates CQI, rank indicator and precoding matrix indicator. As of the writing of this paper, our simulator only supports single-input single-output transmission. Therefore, only the CQI is used in the scheduler. For the CQI choice, the mapping tables described in Section III are used. Currently, only a mapping corresponding to the LTE-A standard is implemented, but new tables for, e.g., 5G NR can be added with ease. Dependent on the chosen scheduler type, the feedback information is then used to find an optimal scheduling decision for future frames.

When all frames are simulated, all results are collected and stored. Based on the spatial and temporal realizations, average values for SINR or user throughput can be calculated. Again, the evaluation of further performance metrics can be implemented and performed based on the stored output of the simulation.

TABLE III
SIMULATION PARAMETERS USED TO COMPARE THE VIENNA LTE-A SL SIMULATOR AND THE VIENNA 5G SL SIMULATOR.

Parameter	Value
base stations	hexagonal layout, 1 ring, 7 BSs
users	50, uniform density
path loss model	COST231 Urban Macro (UMa)
channel model	Pedestrian A PDP
TTIs/slots	100
feedback delay	3
user speed	30 km/h

C. Verification of the Simulator

As already described in Section II-C, numerical simulation tools require verification in order to produce realistic and reliable results. Especially for a SL simulator this is required, due to the abstraction steps that become necessary in order to keep the computational complexity manageable.

The results of the LTE-A SL simulator were already verified through a comparison to the LTE-A LL simulator [18]. In order to perform a verification for the 5G SL simulator, we now compare it to the LTE-A SL simulator, since a more complex scenario can be used than in a comparison to the LL simulator. Thus, also the network geometry can be included in the comparison.

As an example, we choose a scenario with BSs arranged in a hex-grid and place users randomly in the simulation area. The same path loss and channel models are chosen for both simulators and the same number of slots is simulated. Also further parameters are all set to be equal in both cases. The utilized parameter-set is given in Tab. III.

The placement of network objects, as well as user association (and thus also models that affect the large scale fading) are verified by comparing the empirical cumulative distribution functions (ecdfs) of the distances between users to their assigned BS, as well as the wideband SINR (i.e., the SINR not including the microscopic fading). As it can be seen in Figs. 5 and 6, the curves overlap almost perfectly for both cases.

To also verify the functionality of further functions, such as the scheduler and feedback calculation, throughput ecdfs obtained from both simulators are compared. The results can be found in Fig. 7. Once again, the curves show a good match.

D. Example Simulation Scenario

The main advantage of the new simulator is its increased flexibility with respect to defining various types of BSs and users. To showcase this, we present a scenario comprised of a heterogeneous multi-tier network with pedestrian and car users. A spatial realization of such a scenario is shown in Fig. 8. There, purple dots can be identified as car users, traveling along a highway that stretches from left to right

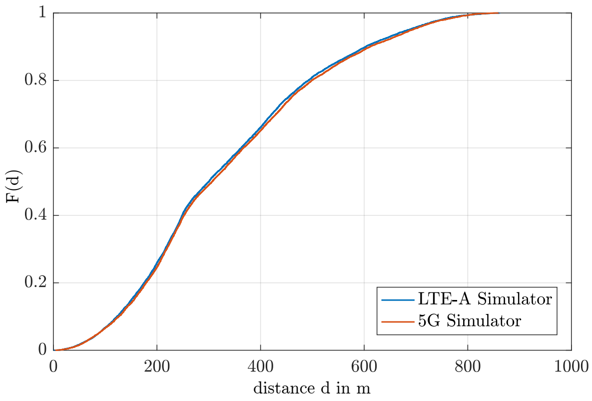


Fig. 5. Comparison of the distances between users and their assigned BS for the Vienna LTE-A and 5G SL Simulator, represented as ecdf of values for all users.

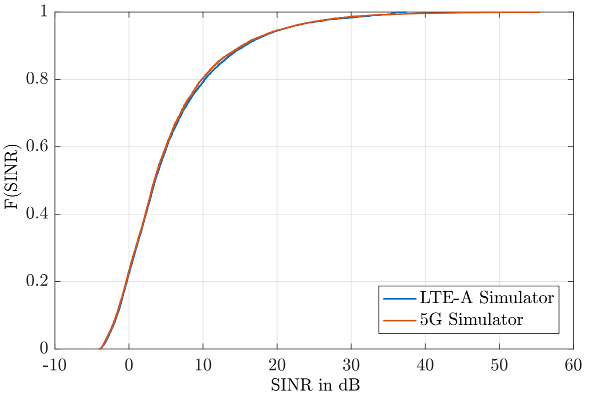


Fig. 6. Comparison of the wideband SINR for the Vienna LTE-A and 5G SL Simulator, represented as ecdf of values for all users.

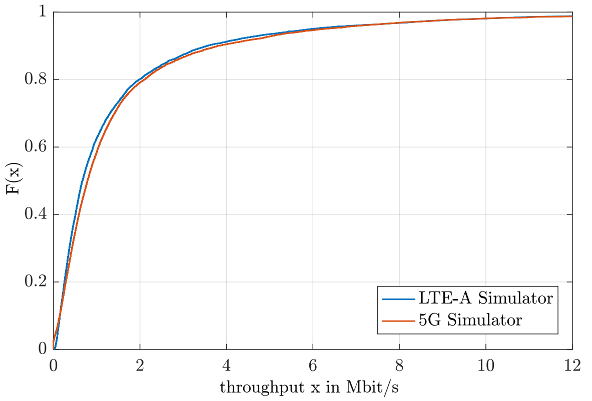


Fig. 7. Comparison of the average user throughput for the Vienna LTE-A and 5G SL Simulator, represented as ecdf of values for all users.

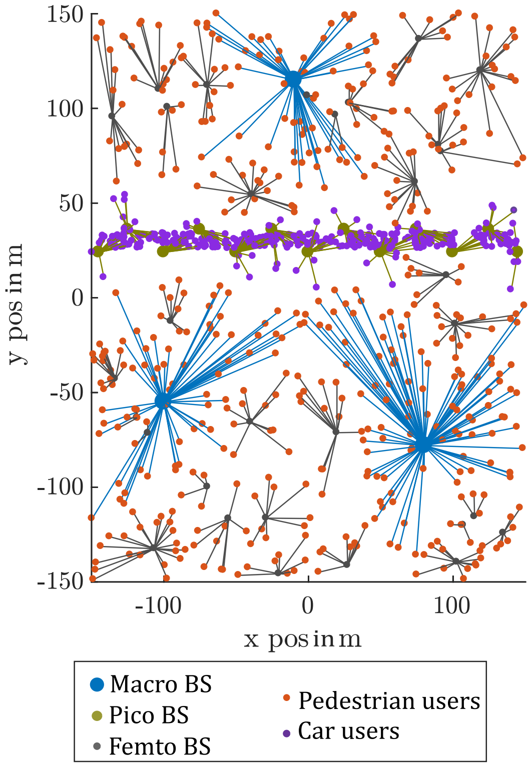


Fig. 8. The simulated scenario with three types of BSs and two types of users. BS-user association based on the maximum received power.

through the simulation area. They are served by pico cells, represented by green dots, that are placed along the highway with equidistant spacing. The pedestrian users, represented by red dots, are randomly placed according to a PPP. There are two more types of BSs, namely macro and femto BSs, that are also placed randomly.

Each user type is assigned their own channel model. Additionally, the path loss model changes, dependent on the type of the serving BS. The connection table is presented in Tab. IV. It is assumed that pico BS are placed along the highway and have LOS towards the car users, why the free-space path loss model with an exponent of $\alpha = 2$ is used. The penetration loss into the cars is neglected. The femto BSs are assumed to be indoors. Therefore, they utilize the appropriate path loss model, defined in [35].

Results from the simulation in terms of average user throughput ecdfs are presented in Fig. 9. It can be seen, that generally, the throughput is better for pedestrian users. This

TABLE IV
MOST IMPORTANT BS PARAMETERS AND LOOK-UP TABLE USED TO DETERMINE SITUATION AWARE PATH LOSS, ACCORDING TO THE BS TYPE

BS type	In-/Outdoor	transmit power	Path loss type
macro	O	40 W	3D-UMa [36]
pico	O	5 W	free-space, $\alpha = 2$
femto	I	0.2 W	Indoor [35]

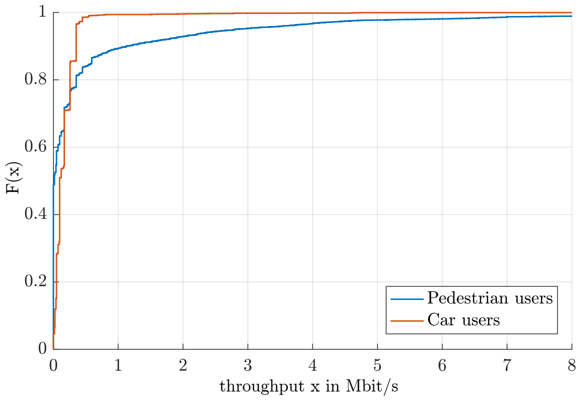


Fig. 9. The resulting ecdfs for pedestrian and car users. The large throughput values for pedestrian users stem mostly from association to femto BSs.

is mostly due to the combined serving of pedestrian users by macro as well as femto BSs. Nevertheless, the presented result is dependent on the chosen user and BS densities.

V. CONCLUSION

Since verification is a key aspect for numerical simulation tools, we consider the process of verification for the Vienna 5G LL Simulator as well as for the Vienna 5G SL Simulator in this contribution. While this ensures that obtained simulation results are meaningful and representative on average for the modeled simulation scenarios for both simulators individually, the fact that results from LL simulation serve as input to the SL simulator renders the verification a coupled problem as well. Therefore, we further describe the interaction between the Vienna 5G LL Simulator and the Vienna 5G SL Simulator in terms of LQM and LPM in this work. This employed method of abstracting and simplifying individual communication links yields a necessary complexity reduction and is shown to be highly flexible in terms of the employed PHY methods. However, it also implies, that the LL simulator has to be verified in a first step, before verification of the SL simulator is considered.

ACKNOWLEDGMENT

This work has been funded by the Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion. The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development is gratefully acknowledged.

REFERENCES

[1] R. N. Mitra and D. P. Agrawal, "5G mobile technology: A survey," *ICT Express*, vol. 1, no. 3, pp. 132–137, 2015, special Issue on Next Generation (5G/6G) Mobile Communications. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405959515300503

[2] S. Schwarz and M. Rupp, "Society in motion: challenges for LTE and beyond mobile communications," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 76–83, May 2016.

[3] H. Ji, S. Park, J. Yeo, Y. Kim, J. Lee, and B. Shim, "Ultra-reliable and low-latency communications in 5G downlink: Physical layer aspects," *IEEE Wireless Communications*, vol. 25, no. 3, pp. 124–130, Jun. 2018.

[4] Institute of Telecommunications, TU Wien. Vienna cellular communications simulators. [Online]. Available: www.tc.tuwien.ac.at/vccs/

[5] E. Zöchmann, S. Schwarz, S. Pratschner, L. Nagel, M. Lerch, and M. Rupp, "Exploring the physical layer frontiers of cellular uplink," *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 1, pp. 1–18, 2016. [Online]. Available: http://dx.doi.org/10.1186/s13638-016-0609-1

[6] M. Rupp, S. Schwarz, and M. Taranetz, *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation*, 1st ed., ser. Signals and Communication Technology. Singapore: Springer, 2016.

[7] S. Pratschner, B. Tahir, L. Marijanovic, M. Mussbah, K. Kirev, R. Nissel, S. Schwarz, and M. Rupp, "Versatile mobile communications simulation: the Vienna 5G Link Level Simulator," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, no. 1, p. 226, Sep. 2018. [Online]. Available: https://doi.org/10.1186/s13638-018-1239-6

[8] M. K. Müller, F. Ademaj, T. Dittrich, A. Fastenbauer, B. R. Elbal, A. Nabavi, L. Nagel, S. Schwarz, and M. Rupp, "Flexible multi-node simulation of cellular mobile communications: the Vienna 5G System Level Simulator," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, no. 1, p. 227, Sep. 2018. [Online]. Available: https://doi.org/10.1186/s13638-018-1238-7

[9] P. Pirinen, "A brief overview of 5G research activities," in *1st International Conference on 5G for Ubiquitous Connectivity*, Nov. 2014, pp. 17–22.

[10] R. Nissel, S. Schwarz, and M. Rupp, "Filter bank multicarrier modulation schemes for future mobile communications," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 8, pp. 1768–1782, 2017.

[11] T. R. Henderson, M. Lacage, G. F. Riley, C. Dowell, and J. Kopena, "Network simulations with the ns-3 simulator," *SIGCOMM demonstration*, vol. 14, no. 14, p. 527, 2008.

[12] N. Nikaein, M. K. Marina, S. Manickam, A. Dawson, R. Knopp, and C. Bonnet, "OpenAirInterface: A flexible platform for 5G research," *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 5, pp. 33–38, 2014.

[13] T. Domínguez-Bolaño, J. Rodríguez-Piñeiro, J. A. García-Naya, and L. Castedo, "The GTEC 5G link-level simulator," in *International Workshop on Link-and System Level Simulations (IWSLS)*. IEEE, 2016, pp. 1–6.

[14] B. Tahir, S. Schwarz, and M. Rupp, "BER comparison between convolutional, turbo, LDPC, and polar codes," in *24th International Conference on Telecommunications (ICT)*, May 2017, pp. 1–7.

[15] Y. R. Zheng and C. Xiao, "Simulation models with correct statistical properties for rayleigh fading channels," *IEEE Transactions on communications*, vol. 51, no. 6, pp. 920–928, 2003.

[16] T. Zemen and C. F. Mecklenbräuker, "Time-variant channel estimation using discrete prolate spheroidal sequences," *IEEE Transactions on signal processing*, vol. 53, no. 9, pp. 3597–3607, 2005.

[17] 3rd Generation Partnership Project (3GPP), "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception," 3rd Generation Partnership Project (3GPP), TS 36.101, Dec. 2017.

[18] C. Mehlführer, J. C. Ikuno, M. Simko, S. Schwarz, and M. Rupp, "The Vienna LTE simulators — Enabling Reproducibility in Wireless Communications Research," *EURASIP Journal on Advances in Signal Processing (JASP) special issue on Reproducible Research*, vol. 2011, no. 1, pp. 1–14, 2011.

[19] 3rd Generation Partnership Project (3GPP), "Technical Specification Group Radio Access Network; NR; Physical layer procedures for data," 3rd Generation Partnership Project (3GPP), TS 38.214, Sep. 2018.

[20] S. Schwarz and M. Rupp, "Throughput maximizing feedback for MIMO OFDM based wireless communication systems," in *IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. San Francisco, CA, USA: IEEE, Jun. 2011, pp. 316–320.

[21] M. Bellanger, D. Le Ruyet, D. Roviras, M. Terré, J. Nossek, L. Baltar, Q. Bai, D. Waldhauser, M. Renfors, T. Ihalainen *et al.*, "FBMC physical layer: a primer," *PHYDYAS, January*, vol. 25, no. 4, pp. 7–10, 2010.

[22] 3rd Generation Partnership Project (3GPP), "Technical Specification Group Radio Access Network; NR; Physical channels and modulation," 3rd Generation Partnership Project (3GPP), TS 38.211, Dec. 2017.

[23] J. C. Ikuno, "System level modeling and optimization of the LTE downlink," Ph.D. dissertation, E389, TU Wien, 2013.

[24] S. Schwarz, C. Mehlführer, and M. Rupp, "Calculation of the spatial preprocessing and link adaption feedback for 3GPP UMTS/LTE," in *6th conference on Wireless advanced (WiAD)*. IEEE, 2010, pp. 1–6.

[25] L. Wan, S. Tsai, and M. Almgren, "A fading-insensitive performance metric for a unified link quality model," in *IEEE Wireless Communications and Networking Conference*, vol. 4. IEEE, 2006, pp. 2110–2114.

[26] X. He, K. Niu, Z. He, and J. Lin, "Link layer abstraction in MIMO-OFDM system," in *International Workshop on Cross Layer Design*. IEEE, 2007, pp. 41–44.

[27] R. Sandanalakshmi, T. G. Palanivelu, and K. Manivannan, "Effective SNR mapping for link error prediction in OFDM based systems," in *International Conference on Information and Communication Technology in Electrical Sciences*. IET, Dec. 2007, pp. 684–687.

[28] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda, "Simulating lte cellular systems: An open-source framework," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 2, pp. 498–513, Feb 2011.

[29] A. Virdis, G. Stea, and G. Nardini, "Simulating lte/lte-advanced networks with simulte," in *Simulation and Modeling Methodologies, Technologies and Applications*, M. S. Obaidat, T. Ören, J. Kacprzyk, and J. Filipe, Eds. Cham: Springer International Publishing, 2015, pp. 83–105.

[30] X. Wang, Y. Chen, and Z. Mai, "A novel design of system level simulator for heterogeneous networks," in *2017 IEEE Globecom Workshops (GC Wkshps)*, Dec 2017, pp. 1–6.

[31] N. Mohsen and K. S. Hassan, "C-ran simulator: A tool for evaluating 5g cloud-based networks system-level performance," in *2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Oct 2015, pp. 302–309.

[32] K. Bakowski, M. Rodziewicz, and P. Sroka, "System-level simulations of selected aspects of 5G cellular networks," in *2015 International Symposium on Wireless Communication Systems (ISWCS)*, Aug 2015, pp. 711–715.

[33] S. Cho, S. Chae, M. Rim, and C. G. Kang, "System level simulation for 5g cellular communication systems," in *2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN)*, July 2017, pp. 296–299.

[34] T. Dittrich, M. Taranetz, and M. Rupp, "An efficient method for avoiding shadow fading maps in system level simulations," in *WSA 2017; 21th International ITG Workshop on Smart Antennas*, March 2017, pp. 1–8.

[35] 3rd Generation Partnership Project (3GPP), "TDD Base Station Classification," 3GPP, TR 25.952, Mar. 2003.

[36] ——, "Study on 3D channel model for LTE," 3rd Generation Partnership Project (3GPP), TR 36.873, Jun. 2015.