IEEE Access
practical innovations : open solutions

Received March 5, 2013, accepted April 16, 2013, published May 10, 2013.

Digital Object Identifier 10.1109/ACCESS.2013.2260371

Pushing the Limits of LTE: A Survey on Research Enhancing the Standard

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This work was supported in part by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, KATHREIN-Werke KG, and A1 Telekom Austria AG.

ABSTRACT Cellular networks are currently experiencing a tremendous growth of data traffic. To cope with this demand, a close cooperation between academic researchers and industry/standardization experts is necessary, which hardly exists in practice. In this paper, we try to bridge this gap between researchers and engineers by providing a review of current standard-related research efforts in wireless communication systems. Furthermore, we give an overview about our attempt in facilitating the exchange of information and results between researchers and engineers, via a common simulation platform for 3GPP long term evolution (LTE) and a corresponding webforum for discussion. Often, especially in signal processing, reproducing results of other researcher is a tedious task, because assumptions and parameters are not clearly specified, which hamper the consideration of the state-of-the-art research in the standardization process. Also, practical constraints, impairments imposed by technological restrictions and well-known physical phenomena, e.g., signaling overhead, synchronization issues, channel fading, are often disregarded by researchers, because of simplicity and mathematical tractability. Hence, evaluating the relevance of research results under practical conditions is often difficult. To circumvent these problems, we developed a standard-compliant open-source simulation platform for LTE that enables reproducible research in a well-defined environment. We demonstrate that innovative research under the confined framework of a real-world standard is possible, sometimes even encouraged. With examples of our research work, we investigate on the potential of several important research areas under typical practical conditions, and highlight consistencies as well as differences between theory and practice.

INDEX TERMS Heterogeneous networks, distributed antenna systems, frequency synchronization, pilot power allocation, multiuser gains, LTE, MIMO, reproducible research.

I. INTRODUCTION

Life without ubiquitous possibilities to connect to the Internet is hard to imagine nowadays. Cellular networks play a central role in our global networking and communication infrastructure. To ensure and even enhance availability, the standardization process of new communication systems is governed by concerns about reliability, interoperability and security, besides trying to improve the performance of current technology. Still, the ever-increasing demand for higher data-rates forces the consideration of novel research results during standardization. Mobile data traffic is predicted to increase 13-fold between 2012 and 2017, culminating in a monthly global data traffic of more than 10 exabytes by 2017 [1]. To sustain such a traffic growth, standardization experts ceaselessly improve wireless networks. In this process, however, innovative research results are frequently met with skepticism, because assumptions made by researchers are sometimes too simplistic and idealistic to reflect the performance under practical conditions. Consider, e.g., spatial interference management techniques like linear multi-user MIMO (MU-MIMO) transmission [2], [3] and interference alignment [4], [5]. While theory predicts tremendous spectral efficiency gains under the assumption of perfect channel state information at the transmitter (CSIT), heavy losses are reported if this assumption is only slightly violated [6], [7], e.g., due to delayed or quantized CSI feedback. Although tailored solutions exist to resolve these problems, e.g., [8]–[11], standardization is still reluctant about investing in the

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CSI feedback, possibly because communication and information exchange between academia and industry is insufficient.

The world's leading cellular networking technology these days is standardized by the 3rd Generation Partnership Project (3GPP), a collaboration between telecommunication associations spread all over the world. Technical specifications for the radio access network technology, the core network and the service architecture are released every few years, constantly evolving the cellular system with a major focus on compatibility between releases. With the introduction of Long Term Evolution (LTE) in Release 8 (2008) [12], an entirely new air interface based on Orthogonal Frequency Division Multiplexing (OFDM) was implemented setting the basis for a 4G capable mobile communication technology, and first LTE networks went on-air in 2009/10. Since then, work on LTE advanced (LTE-A) (i.e., LTE Rel. 10) and beyond is ongoing in the standardization groups to enhance the transmission capabilities of LTE. The basis for downlink MU-MIMO and other non-codebook based precoding schemes was set by extending the reference symbol structure of legacy LTE for user-specific reference symbols [13]. Network densification, captured under the keywords heterogeneous networks, small- and femto-cells and distributed antenna systems (DASs), is recognized as an important means to circumvent the capacity crunch [14]. This has to go hand in hand with improved interference management, i.e., coordinated multi-point transmission and reception (CoMP), to cope with the increased interference between cells [15].

Despite all of these technologies being considered in the standard, their implementation is largely based on very simple concepts. Hence, research work is ongoing in parallel to develop more sophisticated solutions. We provide an overview of such standard related research during the course of this article, summarizing results of other research groups and providing a more detailed view on our own work. Our main focus is thereby on LTE networks, although the same concepts are mostly applicable for WiMAX [16] and WiFi [17] as well.

In trying to classify research work with respect to its practical applicability, theoretical results mostly lag behind due to the coarse abstraction required to facilitate analytical tractability. Such results have their significance in providing upper bounds on system performance, analyzing the potential of new technologies, and opening/identifying new fields for research and engineering activities. Simulations, on the other hand, enable investigations of much more complex, detailed and realistic scenarios, and facilitate comparison of different algorithms under identical conditions. Simulations can give a qualitative understanding of the interplay of different components of the systems, which may not be obtainable otherwise for complexity reasons. Measurements and field trials, finally, avoid all kinds of assumptions and models, thus reflecting reality most closely. Still, the involved expenditure of time, labor and money, and the lack of generality in the obtained results prohibits their application in early stages of research.

The simulation approach is hence adopted by many researchers in combination with theoretical investigations, due to its flexibility and efficiency. Though standardized simulation models exist for parts of the environment, e.g., the wireless channel in cellular communications [18], [19], there is still lots of ambiguity in many simulation parameters left, making it often difficult to reproduce results of other researchers and hampering cross-comparison of different techniques, a circumstance that has been complained about quite openly in [20], [21]. Moreover, the code of such highly complex systems may contain more than 100.000 lines, making thorough testing practically impossible in a reasonably short time. Only working in parallel with many independent research groups and communicating publicly via a web-based forum makes it possible to identify programming bugs and have the code checked independently several times. These facts were the motivation for our group to develop standard-compliant open-source Matlab-based link- and system-level simulation environments for LTE to facilitate reproducibility and information exchange via a common platform.

A. Organization

In Section II, we introduce our link- and system-level simulators and highlight the multitude of scenarios that can be investigated with these tools. Then, in Section III, we provide a review of current physical layer research that is closely related to LTE and LTE-A. We also consider in more detail the impact of imperfect frequency synchronization on the system throughput in this section, and present a pilot power allocation algorithm that efficiently distributes the available transmit power among reference- and data-symbols. Section IV is dedicated to interference in wireless networks. A literature survey gives an overview of state of the art research considering interference management techniques and algorithms for wireless communications. A very simple technique for mitigating the detrimental effects of interference is opportunistic scheduling, i.e., exploiting the interference dynamics to serve users whenever they experience favorable channel conditions. This is considered in Section IV-B. In sections IV-C and IV-D, we give our view on heterogeneous networking architectures by investigating the performance of distributed antenna systems and macro-femto overlay networks.

II. FACILITATING REPRODUCIBILITY

The *Vienna LTE simulators* [22] are a simulation suite for link- and system-level simulation of LTE networks that is developed and extended by our research group since the first specifications of LTE were published in 2008. The simulators are publicly available for download (www.nt.tuwien.ac.at/ltesimulator) under an academic non-commercial use license. They facilitate reproducibility of research results, and contribute to bridge the gap between researchers and standardization experts in LTE and LTE-A.

Since its first release in 2009, the LTE downlink link-level simulator was downloaded more than 16 000 times and is currently (February 2013) in its eighth release. It was also extended to LTE-A and augmented with an uplink version in 2011 [23]. The LTE system-level simulator experienced even more attention, with more than 22 000 downloads, thus confirming the demand for a consistent simulation environment. Details about the physical layer abstraction models employed for system-level simulation can be found in [24], [25].

Other research groups provide similar tools, such as the *Open Wireless Network Simulator* [26] developed at RWTH Aachen University, or the system-level simulator *LTESim* [27] provided by the Telematics lab of Politecnico di Bari, but we are neither aware of the sophistication and accuracy of these tools nor of how active research is conducted around them.

In our research work, the simulators are utilized to investigate cellular networks in varying degrees of abstraction. The simulators play a central role in the collaboration with our industry partners. Consider the example cellular network shown in Fig. 1. It consists of three macro base stations with sectorized antennas, plus additional radio access equipment. Users 1–3 are served in the "classical" way, by attaching the user equipment (UE) to the strongest macro base station and treating other base stations as interferers. The data-transmission can be optimized by focusing on the radio link between a base station and a single UE, which relies on detailed modeling of the physical-layer and requires link-level simulations. Two examples for link-optimization conducted in our group are treated in some detail in sections III-B and III-C, on the subjects of pilot power allocation for channel estimation and carrier frequency synchronization.

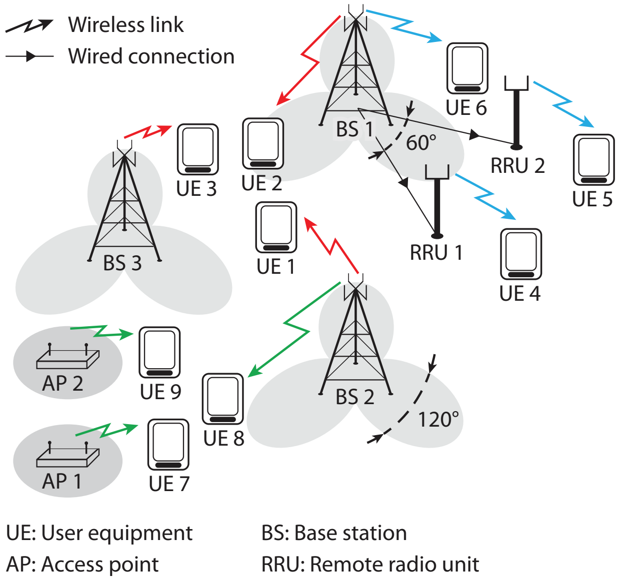

FIGURE 1. Example cellular network consisting of three sectorized macro base stations and additional radio access equipment, visualizing different scenarios considered in our research work.

An alternative perspective for the optimization of cellular communication systems is the network viewpoint. Here, a large network consisting of a multitude of base stations and UEs is considered. To keep the computational complexity of the associated system-level simulations tractable, abstraction of the physical-layer details is necessary. Section IV-B treats multi-user scheduling as an example, confirming the theoretically well-known double-logarithmic growth of the sum-rate with the number of users under the practical constraints that are introduced by the LTE standards, but also showing that the spatial degrees of freedom are not fully utilized by the system.

Extensions of the classical sectorized cellular network architecture to heterogeneous networks, containing different types of radio access equipment, are in the scope of many recent research activities. Two examples are shown in Fig. 1. Users 4–6 are jointly served by a single base station whose transmission capabilities are enhanced by remote radio units (RRUs), forming a so called distributed antenna system (DAS). The performance of different transmission strategies in such distributed antenna systems is evaluated in Section IV-C. In this case, we cannot abstract the physical layer details, because they are necessary to calculate the precoders and beamformers of the considered transmission strategies. To circumvent computational complexity issues in this case, we employ a hybrid of link- and system-level simulations, by augmenting the link-level simulator with an appropriate inter-cell-interference model [28], [29].

Femto cell access points are a popular technique for increasing the spatial reuse of existing cellular networks. Users close to access points are offloaded from the macro cellular network and served by the femto cells (see Users 7–9 in Fig. 1). The benefits of LTE femto cell-enhanced macro networks in terms of user throughput and fairness of the resource allocation are investigated in Section IV-D, by means of system-level simulations.

The link-level simulator can also be beneficially employed to simplify measurement campaigns. In our research group it serves as a front-end for a measurement testbed, generating the base band transmit signal and detecting the received signal. Some recent measurement results investigating the impact of different antenna configurations on the LTE downlink throughput can be found in [30]. Also, the system-level simulator can be used in combination with real measured network data by loading measured channel pathloss maps into the simulator. We successfully employed this feature to confirm observed trends of our industry partners in the real world measured throughput.

III. ENHANCING THE PHYSICAL-LAYER

Recent measurement and simulation based investigations of current cellular communication systems (HSDPA, WiMAX, LTE) have revealed a large performance gap between the throughput achieved in such systems and the theoretical upper bounds determined by channel capacity [31], [32]. Although it is often believed that the potential of the physical-layer is already largely exploited, these investigations show that there is still lots of space for improvement left, even when considering only a single transmitter-receiver pair. This was also observed in [20] who pointed out that innovative PHY research is possible by investigating more realistic mathematical models that consider constraints and suboptimalities of practical systems, e.g., channel estimation errors, power amplifier non-linearities, synchronization errors, realistic CSI feedback algorithms,... Notice though that the accumulated throughput loss of a single link, although significant, is made up of a multitude of small contributions [33]. Hence, large performance gains from a single PHY research front only may not be obtained.

Conducting research on the physical-layer of a wireless communication system requires detailed modeling of the wireless channel and the signal-processing algorithms applied at the transmitter and receiver. In this section, we firstly provide a survey on standard-related PHY research in Section III-A, focusing on LTE and LTE-A. Notice that there exists a huge amount of literature on that topic; hence we can only provide our restricted view and by far not an exhaustive description. We also provide two examples of our research work to establish the utility of the Vienna LTE link-level simulator for PHY investigations. In Section III-B substantial power savings are demonstrated at high user velocities by exploiting the mean squared error (MSE) saturation of well-known channel estimation algorithms in temporally weakly correlated channels. Furthermore, the impact of a frequency estimation error, causing a carrier frequency offset between transmitter and receiver, on the throughput of an LTE system is considered in Section III-C.

A. LITERATURE SURVEY

One important physical-layer research topic for wireless communication systems in the uplink as well as the downlink is channel estimation. The channel estimation error not only impacts the post-equalization signal to interference and noise ratio (SINR) [25], [34] but also the accuracy of CSI feedback estimation and hence the achievable throughput of the system [35]. Important aspects of channel estimation covered in the literature are high-velocity fast-fading scenarios [36]–[38], iterative channel estimation [39], [40], special designs for multi-user and multi base station situations [41], [42] as well as low-complexity solutions [43], [44].

Another topic of practical relevance is the timing- and frequency-synchronization of transmitter and receiver or of multiple transmission points. A frequency synchronization error between transmitter and receiver results in inter-carrier-interference after OFDM signal processing at the receiver [45]. Similarly a synchronization error in the symbol timing leads to inter-symbol-interference [46]. Both effects significantly reduce the achievable throughput of the system, hence accurate synchronization algorithms are required, e.g., [47]–[49].

Also, CSI feedback estimation is important for LTE to achieve the highest throughput in MIMO systems. Here, one has to distinguish between CSI feedback for codebook based precoding and feedback for non-codebook based precoding. The former consists of a precoding matrix indicator and a rank indicator, to select the preferred precoder from a given codebook, and a channel quality indicator to adapt the transmission rate [50]–[52]. Non-codebook based precoding enables more sophisticated transmission strategies like zero forcing (ZF) beamforming [3], block-diagonalization precoding [2] or interference alignment [4], [5]. In this case, mostly explicit CSI feedback is employed, quantizing the wireless channel in some form directly and feeding it back to the base station [8]–[11], [53].

Other topics of interest include advanced receiver designs [54], consideration of power-amplifier non-linearities [55], and efficient reference signal designs [56]–[58].

B. PILOT POWER ALLOCATION

Modern standards for wireless communication systems such as LTE and WiMAX exclusively rely on coherent transmission techniques. Detection of coherently transmitted data symbols requires knowledge of the channel experienced during transmission, which is obtained by channel estimation. The estimates are calculated from known symbols, so called pilot symbols, that are multiplexed within the data symbols. The amount of power assigned to the pilot symbols has a crucial impact on the quality of the channel estimation, which in turn significantly impacts the throughput performance of the system. The channel estimation error leads to an additional noise term in the SINR of the transmission, whose variance is determined by the applied channel estimator and the pilot symbol density and power.

Consider an LTE transmitter which has a certain amount of power available for transmission. The available power is divided between pilot and data symbols. The quality of the channel estimates improves with the amount of power invested into the pilot symbols, thus reducing the noise contribution of the channel estimator. But in turn the power of the data symbols has to be decreased to keep the power budget balanced, degrading the received signal power. Therefore, an equilibrium point in the power assignment between pilot and data symbols exists, in which the SINR is maximized.

The precisely elaborated physical-layer of the Vienna LTE link-level simulator enables an extensive investigation of different pilot symbol power allocation algorithms. The optimal distribution of the available transmit power between pilot and data symbols was derived in [59] and [60] for time-invariant and time-variant channels, respectively. The solution turned out independent of the operating point (signal to noise ratio (SNR)) and of the actual channel realization, making it very robust and applicable in practical systems. In [60] it was realized that in time-variant channels state-of-the-art channel estimators (least-squares and linear minimum mean squared error (MMSE)) exhibit an error-floor, which increases with decreasing temporal channel correlation. Thus, at a given user velocity (which determines the temporal channel correlation in the link-level simulator according to Clarke's model [61]) and operating point, a further increase of the pilot symbol power does not necessarily lead to an improvement in the quality of the channel estimate. Therefore, one might think that more power should be allocated to the data symbols. This, however, does not improve the post-equalization SINR either, because the interlayer interference increases with the data symbol power, due to the imperfect channel knowledge. Based on this insight, a power efficient power allocation algorithm was proposed in [62]. In this algorithm the total transmit power of pilot and data symbols is minimized at a given user velocity and noise power, while constraining the post-equalization SINR not to decline with respect to the case that all available transmit power is used. The case in which all available transmit power is used and equally distributed among pilot- and data-symbols is referred to as unit power allocation.

Fig. 2 demonstrates the performance of the power efficient power allocation algorithm in comparison to unit power allocation, as obtained by link-level simulations. The average user throughput versus user speed for three different antenna configurations $N_t \times N_r \in \{1 \times 1, 2 \times 2, 4 \times 4\}$ is shown in the upper part of the figure. It can be seen that the power-efficient power allocation algorithm achieves virtually the same throughput as the unit power allocation algorithm. The power consumption utilizing the power efficient power allocation algorithm with respect to unit power allocation is depicted in the lower part of Fig. 2. The figure shows that at high user velocities substantial power savings are possible without degrading the throughput performance of the system. Note that LTE is defined to operate up to user velocities of 500 km/h.

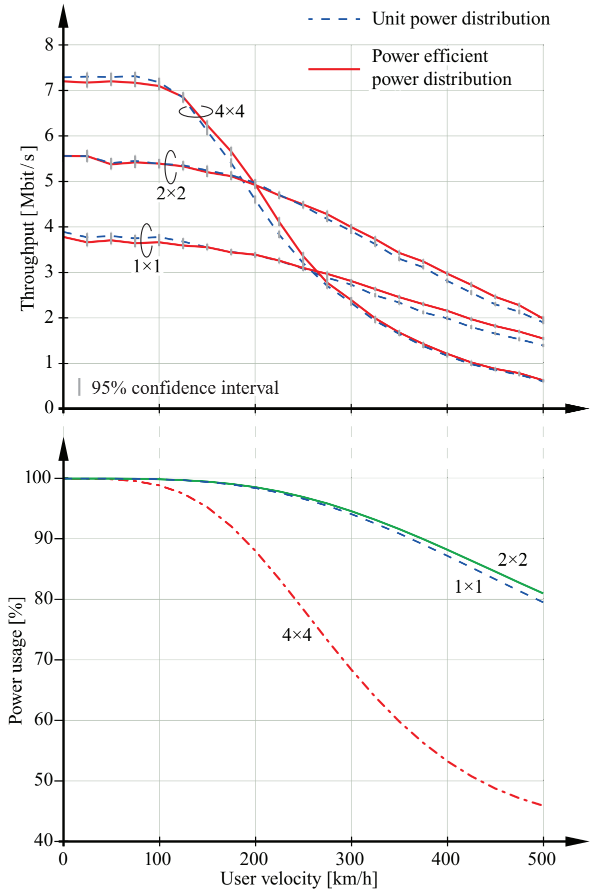

FIGURE 2. Comparison of the average user throughput of an LTE system with unit power allocation for pilot and data symbols, and with power efficient power allocation. The SNR is set to 20 dB. The lower part indicates the power savings of the power efficient power allocation versus unit power allocation.

C. IMPACT OF IMPERFECT FREQUENCY SYNCHRONIZATION

One crucial issue that a novel technique encounters in real world applications is to cope with the physical impairments which are usually not taken into account in simulation-based experiments. For a communication system, typical such examples are an offset between the local oscillators at the transmitter and the receiver, oscillator phase noise or an imbalance between the in-phase and quadrature-phase branches in the front end processing.

Taking the carrier frequency offset (CFO), i.e., the offset between the carrier frequencies at the transmitter and the receiver, as an example, plenty of literature can be found on how to estimate the CFO in the digital signal processing domain. The estimator's performance is usually evaluated in terms of the estimation error, in other words, the MSE. This is shown in the center part of Fig. 3 for two specific examples: (i) the time domain and (ii) the frequency domain estimators of [63], and two different transmit-receive antenna configurations $N_t \times N_r \in \{1 \times 1, 2 \times 2\}$. However, the performance of a communication system is evaluated in terms of the overall coded throughput, encompassing all the signal processing steps applied at the transmitter and receiver, e.g., coding, modulation, equalization, and detection. Therefore, a link performance prediction model is desirable, providing a direct mapping from the residual CFO to the coded throughput. In the following, we show how to utilize such a mapping to estimate the throughput loss caused by the carrier frequency estimation error.

In [45], the authors derive an analytic expression for the post-equalization SINR achieved on a resource element[1] of the LTE downlink with imperfect frequency synchronization. This expression can be exploited to estimate the throughput loss of the LTE system, and thus obtain the desired relation:

1) For a given CFO estimation scheme, determine the estimation performance in terms of the MSE. As shown, e.g., in [45] the MSE is theoretically given by a function which depends on the SNR expressed as MSE(SNR).
2) Calculate the residual CFO $\varepsilon = \sqrt{\mathrm{MSE(SNR)}}$. Utilizing the model of [45], the post-equalization SINR on a resource element r can then be expressed as a function of the CFO, namely $\mathrm{SINR}_r(\varepsilon)$.
3) Estimate the throughput of the system from $\mathrm{SINR}_r(\varepsilon)$.

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[1] In LTE a resource element denotes the basic unit of physical OFDM time-frequency resources.

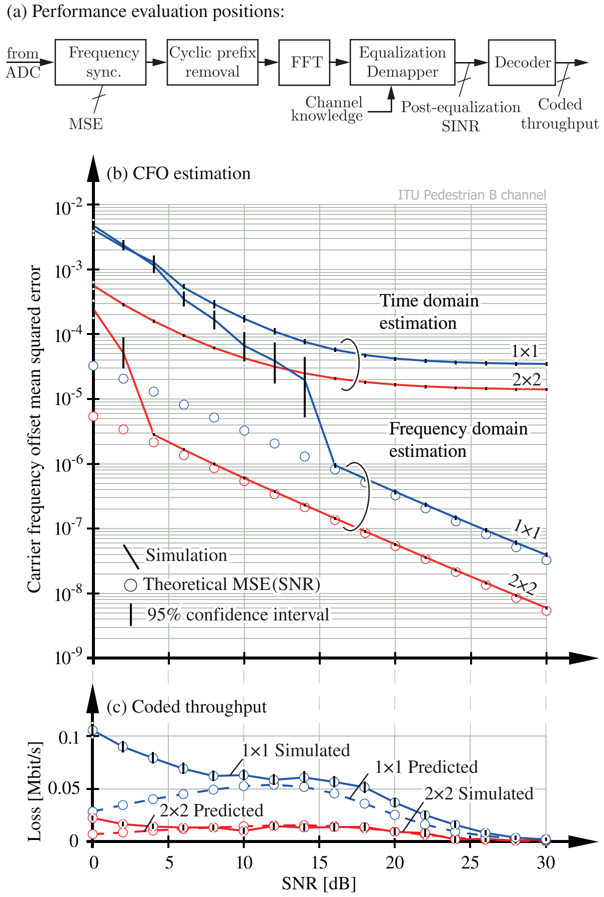

FIGURE 3. **(a) The three performance evaluation positions in the receiver signal processing chain. (b) MSE performance of the carrier frequency synchronization scheme in [63]. (c) The predicted and simulated coded throughput loss resulting from the residual estimation error in (b).**

In general, pre-computed mapping tables valid for the considered system (e.g., obtained from link-level simulations) can be employed to map the post-equalization SINR to a corresponding throughput value. Here, we are only interested in the throughput loss compared to the case of perfect synchronization. In this case, we can employ the bit-interleaved coded modulation (BICM) capacity to estimate the throughput $f\,(\mathrm{SINR}_r(\varepsilon))$, since LTE is based on a BICM architecture. The imperfect channel code will cause an offset in the absolute value of the estimated throughput, but this offset approximately cancels out when calculating the throughput loss $\Delta B = \sum_r f\,(\mathrm{SINR}_r(0)) - \sum_r f\,(\mathrm{SINR}_r(\epsilon))$.

The Vienna LTE link-level simulator enables such investigations and greatly facilitates a standard compliant validation. In the bottom part of Fig. 3, the predicted loss in terms of the coded throughput is compared to the results obtained by means of extensive link-level simulations. The figure confirms that the prediction model performs well as soon as the MSE follows the theoretical MSE(SNR) relation. The large deviation of the 1×1 system at low SNR can be explained by the deviating performance of the employed synchronization algorithm from the theoretical curve, as shown in the center part of Fig. 3.

IV. TREATING INTERFERENCE IN CELLULAR NETWORKS

Many research efforts currently concentrate on the interference between multiple transmitter and receiver pairs. We review some of this work with focus on applicability in practical systems in the near future in Section IV-A.

A robust way to deal with interference is opportunistic scheduling, which exploits the interference dynamics to serve users whenever they experience good channel conditions. This is investigated in Section IV-B using system-level simulations.

With sufficient CSIT, sophisticated signal-processing algorithms can be applied before transmission to avoid/minimize interference between several nodes. In Section IV-C multi-user beamforming in DASs with perfect and quantized CSIT is considered, revealing large throughput gains in comparison to single-user MIMO (SU-MIMO) systems.

Finally, in Section IV-D the impact of interference caused by femto-cell deployments on existing macro cellular networks is explored with the aid of the Vienna LTE system-level simulator, in terms of user throughput and resource allocation fairness.

A. LITERATURE SURVEY

An effective way to deal with the exponential growth in wireless data traffic is the deployment of small-size low-power base stations, so called femto-cells, within the usual network of macro base stations. Special attention must then be paid to the management of interference between different layers of the resulting heterogeneous network. Also, to improve coverage and to mitigate shadowing- and penetration losses, the network can be extended by low-cost relay nodes and RRUs, further complicating the inter-cell-interference situation. There are many approaches for solving the interference problematic. Following the notation introduced with CoMP in LTE-A, these methods can basically be classified as coordinated scheduling, coordinated beamforming or joint processing techniques.

With coordinated scheduling, base stations exchange control information via the X2 interface, to coordinate the assignment of time-frequency resources. Some recent examples of coordinated scheduling algorithms can be found in [64], [65]; a thorough overview of multi-cell scheduling in LTE is presented in [66]. Coordinated beamforming also relies on the exchange of control information between base stations. Here the goal is to form transmit beams such as to minimize the power of interfering signals and maximizing the power of the intended signals. Typically, this leads to optimization problems involving SINR or signal to leakage ratios [67]–[69]. Also, interference alignment falls into this category. Joint processing, finally, requires not only an exchange of control information, but also an exchange of the user data. With these techniques, the transmit antennas of several base stations form a virtual MIMO system and jointly transmit data to users, effectively eliminating cell boundaries. Although such methods can achieve the best performance, they also suffer from the highest CSI feedback overhead and backhaul load. Some of the latest proposals can be found in [70], [71]. A more comprehensive overview of several CoMP techniques is presented in [72].

B. SCHEDULING AND MULTI-USER GAIN

When a single transmission link is considered, time and frequency diversity can be exploited to increase the throughput and reliability of the data transmission. In a practical cellular network that serves not only a single user but a multitude of them, multi-user diversity can additionally be utilized to increase the total throughput of the cell. In combination with the spatial degrees of freedom added by a MIMO system, theory states that the throughput gain due to multi-user diversity follows an $N_t \log\log k$ rule with the number of concurrent users k [73], where N_t is the number of transmit antennas.

The theoretical $N_t \log\log k$ rule, although useful as an upper bound on the achievable diversity, is not directly applicable to the throughput of an LTE link, because other parasitic effects encountered in a practical system diminish parts of the promised gains [32], e.g., a growing pilot symbol overhead with increasing number of transmit antennas and a limited choice of possible precoding matrices in MIMO systems. Hence, there is a need for realistic throughput simulations.

Simulations of large cellular networks, with many cells and users being present, are very computationally demanding. If implemented via link-level simulations, a single simulation of that kind could last several months. By applying physical-layer abstraction models, it is possible to reduce the complexity of such system-level simulations, without significantly compromising the accuracy of the results [24].

Fig. 4 shows simulation results obtained with the Vienna LTE system-level simulator, comparing the performance of several scheduling algorithms in an LTE network. The left-hand side results are obtained in a SISO system, while the right-hand side performance is achieved in a MIMO system with $N_t \times N_r = 2 \times 2$ employing LTE's closed-loop spatial multiplexing (CLSM) mode, using the CSI feedback algorithms of [50]. The following scheduling schemes, implemented according to [74], are employed:

1) Best CQI scheduling assigns resources to the users with the best channel conditions only. This algorithm is the practical counterpart to the theoretical cell throughput upper bounds, but it achieves the lowest fairness in terms of distributing resources among users.
2) Proportional fair scheduling aims at increasing fairness and avoiding the user starving issue encountered in the best CQI scheduler, by scheduling users whenever their channel conditions are good with respect to their own average channel quality.
3) The round robin scheduler equally distributes resources among users. While the former two algorithms are opportunistic in nature, serving users whenever they experience good channel and interference conditions, this latter algorithm ignores any channel state information and thus does not make use of the available diversity.

An adaptation of the $N_t \log\log k$ rule is employed to quantify the spatial multiplexing and multi-user gains of a practical system, by introducing a scaling factor a for the multiplexing gain and a diversity gain loss factor b for the multi-user diversity. The results for the considered LTE system show a multiplexing gain factor (N_t/a) of 1.56 for an $N_t \times N_r = 2 \times 2$ system, and a gain of 2.66 for a 4×4 antenna configuration compared to the SISO case, thus considerably below the theoretical values of 2 and 4, respectively. A similar analysis

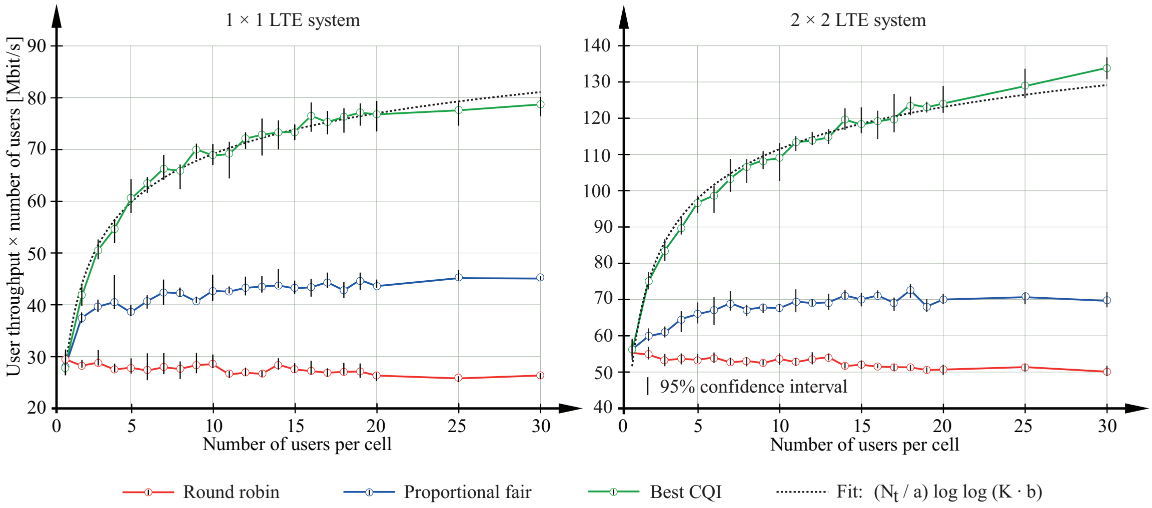

FIGURE 4. Multi-user gain simulation results for a SISO (left) and 2 × 2 closed-loop spatial multiplexing LTE MIMO (right) configuration. Solid line: throughput results. Dashed line: $\log\log k$ approximation.

applied to proportional fair scheduling shows the same gains relative to the SISO case.

Such an analysis of the multi-user gains of LTE can serve as the basis for the extension to more complex setups, such as ones including distributed antennas or femto cells.

C. DISTRIBUTED ANTENNA SYSTEMS

A DAS is a cellular networking architecture in which several transmission points, controlled by a single base station, are geographically distributed throughout the network. DASs make use of RRUs to extend the base stations' central antenna ports (cf. BS 1 in Fig. 1). Coherent data transmission from all antennas is enabled by a high-bandwidth low-latency connection between the RRUs and the base station, thus making spatial multiplexing of several data-streams and/or users possible. Several publications have established the theoretical potential of DASs for improving the network capacity, reducing the outage probability and improving the area spectral efficiency (e.g. [28]), but investigations taking into account the constraints imposed by a practical system, e.g., channel coding, limited feedback, are scarce in literature (e.g. [29], [75]).

Simulations of advanced transceivers, especially for MU-MIMO transmission, as well as limited feedback algorithms require detailed knowledge of the users' channels, and are thus hardly amenable to system-level abstraction. Therefore link-level simulations appear as the appropriate choice, but are complicated by the fact that multiple base stations should be simulated to account for the changes in the out-of-cell interference environment caused by RRUs. In our simulations, we strike a compromise between computational complexity and accuracy, by employing the link-level simulator to explicitly simulate three cells and considering interference from more distant base stations with the out-of-cell interference model of [28]. For that purpose, the Vienna LTE-A link-level simulator is extended with a distance-dependent pathloss model and a macroscopic fading model, determining the SNR of a user based on its position (see [75] for details).

Fig. 5 shows simulation results obtained with this hybrid link/system-level simulation environment. A network of base stations arranged in a regular hexagonal grid is considered. Each base station employs 120° sectorized transmit antennas and thus serves three cells. Additionally, each cell contains two RRUs at a distance of 2/3 the cell radius (see BS 1 in Fig. 1). The throughput performance with and without RRUs is shown in the left and right parts of Fig. 5, respectively. Without RRUs $N_t = 8$ transmit antennas are collocated at the base station, and with RRUs two antennas are placed at each RRU leaving four collocated antennas for the base station. Each receiver is equipped with $N_r = 4$ antennas.

In the simulations, different SU-MIMO and MU-MIMO transceivers are compared, assuming either perfect or quantized CSIT. In SU-MIMO, users are served on separate time/frequency resources, thus avoiding in-cell interference between users. In a MU-MIMO system, users can additionally be multiplexed in the spatial domain. In this case, interference can be avoided by appropriate pre-processing at the transmitter, e.g., employing the simple linear precoding technique known as ZF beamforming [3]. The advantage of such techniques is that the potential spatial multiplexing gain is only limited by the number of transmit antennas, whereas in SU-MIMO the minimum of N_t and N_r is the decisive factor. Additionally, high receive antenna correlation often limits the spatial multiplexing capabilities of hand held devices strictly below N_r, a problem that is altogether circumvented in MU-MIMO because different users typically experience uncorrelated channel conditions. But there is also a downside to MU-MIMO: Perfect interference-cancellation is only achieved with perfect CSIT, otherwise residual interference impairs the transmission. Note that we restrict the MU-MIMO system to transmit at most one stream per user for simplicity.

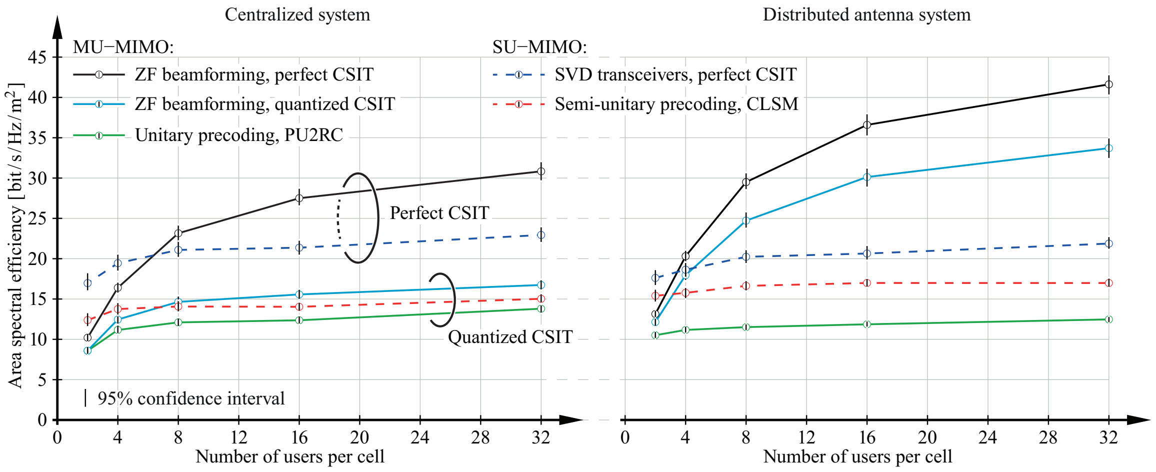

FIGURE 5. **Comparison of the area spectral efficiency obtained in a cellular network without (left-hand side) and with (right-hand side) distributed antennas versus the number of users per cell. The performance with different transceivers and CSI feedback algorithms is compared. The total amount of transmit antennas per cell equals eight. The users are equipped with fourss receive antennas.**

With perfect CSIT, Fig. 5 shows that ZF beamforming based MU-MIMO outperforms SU-MIMO with capacity achieving singular value decomposition (SVD) based transceivers, as soon as there are enough users per cell (≥ 8) to exploit the spatial multiplexing capabilities of the base station. Considering quantized CSIT, ZF beamforming performs similar to LTE's CLSM in the centralized system, while in the DAS a large throughput gain is achieved. This gain is enabled by investing the available feedback bits in those antennas of the distributed antenna array that experience a small macroscopic pathloss, thus exploiting the macro-diversity of the DAS. On the other hand, MU-MIMO with unitary precoding based on per-user unitary beamforming and rate control (PU2RC) achieves a lower throughput than SU-MIMO in both systems, because it cannot exploit the macro-diversity. Note that all considered algorithms have the same feedback overhead (an 8 bit memoryless quantization codebook is used in all cases). For details on the considered transceiver architectures and feedback algorithms the interested reader is referred to [29], [76].

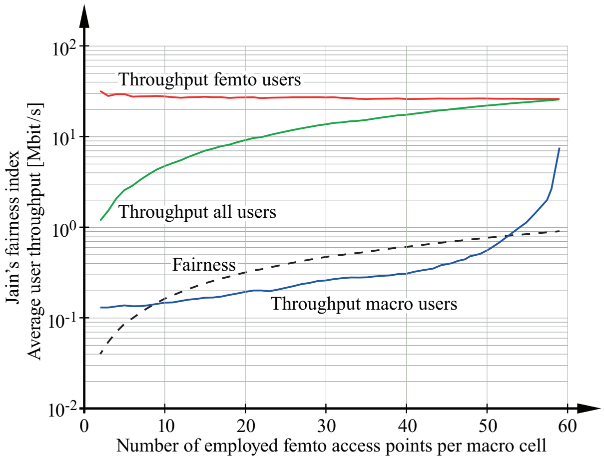

FIGURE 6. **Comparison of the average user throughput achieved by macro-cell users, femto-cell users and both types combined versus the number of femto access points per macro-cell. Also shown is the fairness of the resource allocation in terms of Jain's fairness index.**

D. MACRO-FEMTO OVERLAY NETWORKS

One of the most efficient methods to enhance capacity in a macro cellular network is to minimize the distance between transmitter and receiver [77]. This can be realized with smaller cell sizes and achieves the twofold benefits of increased spatial reuse and improved link quality. However, it comes at the cost of additional interference and required infrastructure. Femto-cells are user-deployed low-power base stations, which offer an economical way to realize small cells in existing macro cellular networks. Since they primarily belong to the unplanned part of the network, it is one of the network providers' major concerns, how the link quality of macro-cell attached users is influenced by a femto-cell deployment. We investigate this question by enforcing two approaches:

1) **Stochastic system model**: In order to carry out system-level simulations, it has been agreed in standardization meetings on models, such as the dual-stripe or the 5×5 grid model [78]. Although these models improve reproducibility, they do not meet scientific researchers' claim for analytical treatability. For this reason, we incorporate femto-cell deployments in our LTE system-level simulator based on *stochastic geometry*. We utilize Poisson point- as well as cluster-processes, which not only reflect the opportunistic placement of femto-cells, but also provide analytically tractable expressions for performance metrics like outage probability and SINR [77], [79]. The results obtained with these ''simple'' models indicate the same trends as the more elaborated environments mentioned above.

2) **Fairness metric**: Based on the stochastic models, we investigate *how many femto-cells can be beneficially deployed in an existing macro-cell*, which arises the prior question: *Beneficial in which sense*, which relates to the question posed in [20], if capacity is really the only metric that should be considered during system optimization.

   In our setup, clusters of users are spread homogeneously over the macro-cell area (according to a Poisson cluster process). Then, one by one, femto-cell access points are added to the network and placed at the center of these clusters. Thus, an increasing amount of users is in coverage of a femto-cell while the total number of users remains constant. Fig. 6 depicts simulation results for the average user throughput (middle solid line) plotted versus the femto-cell density, i.e., the number of employed femto-cell access points per macro-cell. The curve indicates performance improvements for an increasing number of femto-cells. However, it conceals the imbalance of femto-cell and macro-cell user throughput, as shown by the upper- and lower solid line in Fig. 6, respectively. Therefore, we emphasize the importance of a fairness metric to quantify the distribution of the throughput values among the users. In our work, we utilize Jain's fairness index [80], as shown by the dashed line in the figure.

Succinctly, we stress the significance of incorporating various metrics into the performance assessment of heterogeneous cellular networks, and encourage to apply stochastic geometry for the system models of such networks. A more detailed investigation of femto-cell deployments in user hotspot scenarios can be found in [81].

V. CONCLUSIONS

To sustain the exponential growth in mobile data-traffic currently experienced by network operators all over the world, a close cooperation between researchers and standardization/industry experts is required, to identify key technologies that can cope with this demand in the near future. In this article, we present our approach to bridge the gap between researchers and practitioners working on LTE cellular networks by means of the *Vienna LTE simulators*, a standard-compliant open-source Matlab-based simulation platform. The simulators facilitate a standard-compliant validation of novel research results and simplify the evaluation of such results in terms of their significance for practical systems. Furthermore, a unifying platform greatly improves the reproducibility and comparability of different algorithms, by removing uncertainties in the multitude of simulation parameters encountered in such complex systems.

Throughout the article we provide an overview of LTE standard-related research efforts pursued by scientists and engineers world-wide. We also demonstrate the capabilities of the *Vienna LTE simulators* with examples of the research-work conducted in our group with the aid of the simulators. Topics such diverse as pilot-power allocation and frequency synchronization, multi-user scheduling and beamforming, and heterogeneous networking architectures can be effectively treated and investigated with the simulator suite.

We thus encourage researches and engineers, whose field of work is related to LTE/LTE-A, to take a closer look at the *Vienna LTE simulators* and find out whether they can benefit from using this platform.

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