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Modular System-Level Simulator Concept for OFDMA Systems

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ABSTRACT

Modeling and simulation is essential for performance evaluation of wireless systems and specific algorithms used, for instance, during resource allocation. For current and future wireless systems, several properties have to be considered such as data traffic, frequency selective fading channels, and radio resource management. Throughout this article, a new system-level simulator concept is presented for packet switched systems using OFDMA, which is called snapshot-based SLS and represents a compromise between state-of-the-art static and dynamic SLSs. The proposed methodology only considers short time intervals within the busy hour by their statistics so that RRM and data traffic can be considered, as in dynamic SLS, but with lower computational complexity. In this article a description is given of how the cellular setup and traffic generation are performed for the proposed snapshot concept. Furthermore, a new methodology is proposed for a quality measure of resource units that is applicable to future wireless systems using an interleaved subcarrier allocation. Exemplary simulation results show that the developed concept is able to evaluate the performance of OFDMA systems considering the impact of, for example, data traffic and resource allocation strategies.

INTRODUCTION

It is essential to have accurate performance predictions available if wireless systems must be modeled or the performance of radio resource management (RRM) algorithms, such as resource allocation (RA), must be evaluated. For state-of-the-art circuit-switched systems like Global System for Mobile Communications (GSM), the Erlang B equation describes the relationship between the amount of available resources, traffic load (i.e., the amount of active users), and blocking probability [1]. For current and future packet-switched systems, more parameters have to be considered. Resources are no longer allocated exclusively to one user. Instead, different scheduling and RA strategies can be applied [2]. The amount of transmitted data per resource depends on the channel conditions since link adaptation is performed. Multimedia traffic such as download or Web browsing traffic leads to varying traffic load conditions. Blocking is no longer critical if data traffic without or with low delay sensitivity has to be served (e.g., download or Web browsing traffic). Nevertheless, users want to achieve a certain guaranteed data rate to be satisfied [3].

Analytical expressions of the system performance are hard to formulate. Therefore, accurate system-level simulations (SLSs) have to be performed to get system performance results. In general, SLSs become very complex and time consuming if all parameters are considered. Based on the requirements of the evaluation, several SLS concepts are possible. The two common concepts are known as static SLS and dynamic SLS ([4], references therein].

Static SLSs are well suited to obtain results about the system capacity. Static SLSs lack time dependencies so that RRM algorithms or small-scale fading can only be considered by average values. To develop and evaluate RRM algorithms, dynamic SLSs have to be used. The time resolution in a dynamic SLS has to be set to the time period of the property that is investigated. For instance, to investigate RA in a system using time frames for transmission, the time resolution has to be set to the frame duration. While in a static SLS only stationary users with fixed bit rates are assumed, and small-scale fading and RRM algorithms are only considered by their average value, in dynamic SLSs small-scale fading and RRM algorithms are modeled in detail as well as call and packet arrival processes and user mobility. Therefore, dynamic SLSs are usually very complex and need great computational effort due to the long time window.

Only systems using orthogonal frequency-division multiple access (OFDMA) are considered in the following, because OFDMA is a promising candidate for future cellular systems due to favorable properties [5]; for instance, WiMAX and Long Term Evolution (LTE) use OFDMA. Those systems are packet-switched to cope with multimedia traffic. Therefore, sophisticated RA and link adaptation strategies gain importance. Furthermore, it can be observed that these sys-

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tems have to be flexible (e.g., regarding available system bandwidth [1]). In WiMAX this can be achieved by using different numbers of subcarriers with constant subcarrier spacing. Simulation and modeling of these systems requires that properties like scalable bandwidth, RRM algorithms and data traffic be considered.

Throughout this article, we present a new snapshot-based SLS concept called OFDMA-based network performance simulator (ONe-PS). The proposed concept is designed especially for OFDMA networks and reduces the computational complexity compared to a dynamic simulator, but evaluation of RRM algorithms with data traffic models and adaptation to different system requirements is still possible. Random intervals are cut out of the busy hour and considered in ONe-PS. The proposed concept leads to modifications of the cellular setup and traffic generation compared to dynamic SLSs, so independent snapshots can be generated that fulfill the statistical properties of the busy hour instead of modeling the user movement and data traffic in a time continuous fashion. Additionally, an information theoretic quality measure is proposed for resource units (RUs) that can be allocated to users that is independent of a specific system technology. The proposed quality measure can be applied to different technologies such as WiMAX or LTE. The proposed quality measure describes average performance assuming that only one modulation and one code rate is used on each subcarrier of the RU. The quality measure is also used to perform RRM.

The remainder of the article is organized as follows. In the next section, the proposed snapshot based concept of ONe-PS is presented and compared with the state of the art static and dynamic SLSs. The cellular setup for the new concept is described in the following section. We then give an overview about generation of data traffic when using the proposed snapshot approach. The definition of the RU used during RRM is depicted in the following section. The methodology for the quality measure for RUs and the link to the system-level interface used in ONe-PS are then presented. Some performance results are given; and finally, conclusions are drawn.

System-Level Simulator Concept

In this section the proposed concept of ONe-PS is described. For ONe-PS, a compromise between static and dynamic simulation is developed, which is called snapshot-based SLS. The snapshot approach leads to lower computational complexity than a dynamic simulation due to consideration of independent short intervals of the busy hour. However, it provides more functionality than static simulation due to consideration of such things as data traffic models. A snapshot is a time interval selected randomly from the investigated busy hour. If the snapshot duration is short, some properties can be simplified to reduce the computational complexity. For instance, user movement has almost no influence, so path loss and shadowing of a user can be assumed to remain constant. On the other hand, the snapshot includes enough frames so that RRM algorithms can be evaluated and data traffic models considered. Each snapshot contains statistical properties describing the busy hour, and a certain number of snapshots have to be considered to achieve reliable results. Within a snapshot the granularity is given by the frame or symbol duration depending on the system configuration that shall be investigated.

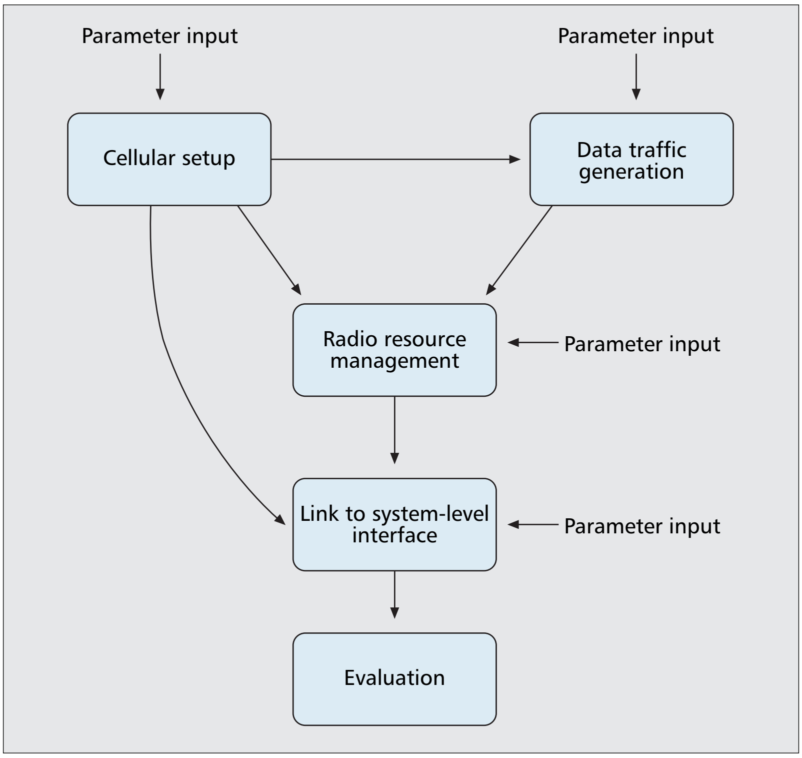


Figure 1. *Modular structure of ONe-PS.*

Of course, ONe-PS also has a modular structure to fulfill the requirements concerning simulation and modeling of future wireless systems. The modules can be adapted depending on the considered system. The five modules and their interaction can be found in Fig. 1. There is one module for the cellular setup of the simulation, including propagation and channel models, where, for instance, the signal-to-interference-plus-noise ratio (SINR) is calculated and provided to the RRM module. The second module is responsible for the generation of data traffic and provides data traffic volume to the RRM module. Between the cellular setup and traffic generation modules, the amount of users per cell is exchanged so that for each user one SINR value and one traffic pattern are derived. Within the RRM module, transmit buffers for users are available and resources used for transmission are provided (e.g., to perform RA). A frame is built that is transferred to the link to system-level interface module. In the link to system-level interface module, transmit conditions given by the cellular setup and actual channel conditions are considered to determine the data rate of the transmitted data blocks. The results of the link to system-level interface module are collected and processed in the evaluation module.

Cellular Setup

In this section the impact of the snapshot concept on the cellular setup is described. Usually in dynamic SLSs, path loss and shadowing are cal-

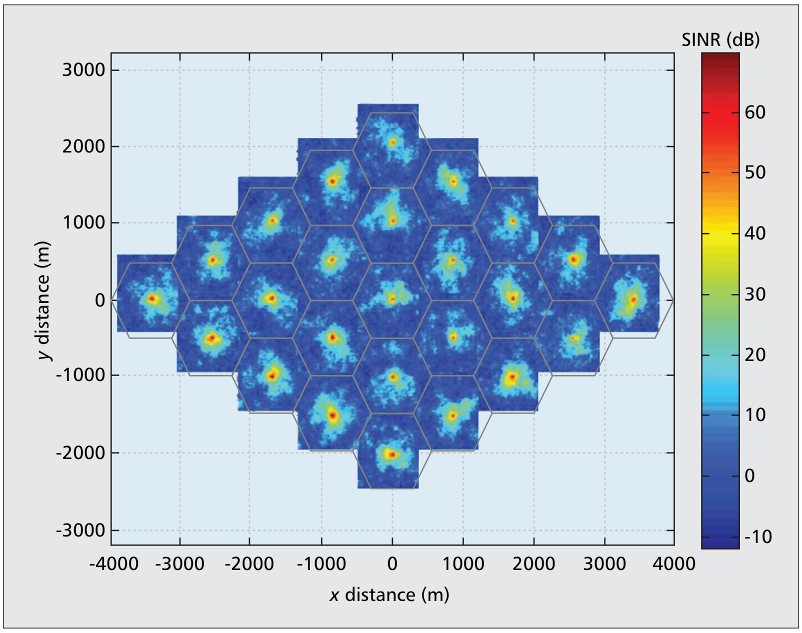


Figure 2. *SINR in the investigation area due to path loss and shadowing in a regular cell structure.*

culated on demand and have to be updated if the subscriber station (SS) moves through the investigation area. Due to the proposed snapshot concept, path loss and shadowing can be assumed to be constant during each snapshot. Only fast fading conditions vary during the snapshot. Therefore, path loss including shadowing can be calculated based on the distance between the base station (BS) and SS in advance of the snapshot [6, 7]. To avoid border effects due to a limited investigation area, a wraparound technique is used where the investigation area is mapped onto a torus [6].

In ONe-PS a pool of possible path loss and shadowing values between SSs and BSs is generated in advance and stored in a file. For each snapshot, the values of the active SSs are taken randomly from the pool. Due to the high amount of possible combinations, the pool does not need to be very large to generate independent snapshots that achieve statistical reliability. This reduces the computational complexity. Figure 2 shows the SINR due to path loss and shadowing in the downlink for different positions as the outcome of the cellular setup module. A specific investigation area for a system with omnidirectional antennas, equidistantly spaced BSs, and all BSs transmitting with equal transmit power is considered. The path loss is calculated with a path loss coefficient of 3.5, and shadowing is modeled by a log normally distributed random variable with standard deviation of 8 dB and a correlation distance of 150 m.

Traffic Generation

In this section the data traffic generation model for the proposed snapshot-based SLS concept is described. Data traffic is an important factor that has to be considered for modeling and performance evaluation of wireless networks. One simplification that is often used is the full buffer traffic model [8]. With full buffer traffic, it is assumed that each SS in the system always has enough data available so that all allocated resources can be used for transmission. With full buffer traffic, a cell is fully loaded as long as one SS is active. It is assumed that all SSs in the scenario are active for the same duration. With realistic data traffic models, it can be observed that SSs with low SINR remain longer in the system than SSs with high SINR. Furthermore, the amount of data available for transmission varies over time. Therefore, results obtained assuming the full buffer traffic model lead to better performance results and are more optimistic (e.g., in terms of cell throughput) than those obtained with realistic traffic models [8, 9].

Multimedia data traffic models are very important for the performance evaluation of wireless networks. A lot of appropriate and tested models for different applications such as download, Web browsing, and speech traffic can be found in evaluation methodologies of different regulation bodies, such as the Third Generation Partnership Project 2 (3GPP2) or European Telecommunications Standards Institute (ETSI). Static SLSs do not usually consider traffic modeling due to complexity. In conventional dynamic SLSs, data traffic is modeled in a time-continuous fashion. Using a birth process (e.g., Poisson process), new sessions are generated and sessions vanish from the system after transmitting all data.

A different traffic generation model is necessary for the snapshot-based SLS concept proposed in this article. Only a snapshot of the busy hour is considered. Therefore, statistics are necessary that describe each snapshot. The main problems are to define the buffer occupancy, the number of SSs that are active at the beginning of the snapshot, and termination of SSs during the snapshot. The buffer occupancy at the beginning of the snapshot is a random variable given by the data size of the traffic model. The number of active SSs is obtained by the session duration and the arrival process considered. An SS terminates its session depending on the duration for which it was already active before the snapshot described by the session duration of the traffic model and buffer occupancy statistics, indicating how much data is still left for transmission. The number of SSs becoming active during the snapshot depends on the arrival process [3]. For the results of a specific SS (e.g., outage), the activity duration during the snapshot is considered, and the results are weighted by the duration this SS is active during the snapshot, so SSs that are only active for a very short time have less impact on the results than SSs that are active for the whole snapshot duration. The arrival of new packets at the BS is modeled as in a conventional dynamic SLS, and the frequency of the packet arrival is called the service data rate (SDR). It is assumed that a predefined fraction of the SDR has to be achieved as active session throughput to keep the user satisfied and the quality of service (QoS) requirement fulfilled.

Radio Resource Management

RRM is an important issue for future wireless systems, and there is a lot of ongoing research in the area of RA algorithms [2]. It is not the focus of this article to derive optimal RA algorithms; rather, a few state-of-the-art algorithms are considered. The focus is on the implementation of RRM algorithms so that the impact of RRM on system performance can be investigated. Therefore, an RU is defined in ONe-PS representing the smallest unit that can be allocated to an SS and is defined by frequency bandwidth, time duration, and space. The RU represents a slot in WiMAX as well as a resource block in LTE. Both adaptive transmit modes with blockwise subcarrier allocation (e.g., adaptive modulation and coding in WiMAX) and diversity transmit modes with distributed subcarrier allocation (e.g., partial usage of subcarriers in WiMAX) can be modeled.

For each RU, only one modulation scheme is used, and encoding is performed over the whole RU. Therefore, one quality measure is necessary for each RU. The methodology to derive the quality measure proposed in this work is described in the next section. If the sender is aware of the quality measure, RA and link adaptation can be performed for each RU based on this quality measure.

Furthermore, with the RU concept used for ONe-PS, it is very easy to adapt the SLS design to the requirements of future wireless systems. For instance, the WiMAX standard, IEEE 802.16, gives different possibilities for the OFDMA physical layer as to which system bandwidth, number of subcarriers, and frame duration can be used. Based on the assumptions made for system bandwidth, number of used subcarriers, or frame duration, in ONe-PS only the amount of RUs has to be adjusted. Even multiple-antenna systems can be investigated with this concept, by modeling the spatial component as another layer of RUs. This makes ONe-PS a scalable SLS tool not limited to one specific system design with, say, fixed system bandwidth or frame design.

Link to System-Level Interface

As mentioned in the previous section, it is necessary to determine a quality measure for each RU. The information theoretic methodology used to derive the quality measure in ONe-PS is described in this section, including the interface that maps link-level results to the system-level evaluation.

Each RU may contain several subcarriers that may be physically neighbored or distributed over the whole system bandwidth. If the subcarriers are physically neighbored, it can be assumed that the fading channel is constant over the whole RU, and the performance of the RU can be described, say, by one pilot subcarrier located in the center of the RU. If the subcarriers are distributed over the whole system bandwidth as, for instance, in the default transmit mode of the WiMAX system, frequency diversity is achieved. In this case the performance of one RU containing several subcarriers can no longer be described by one pilot subcarrier.

An effective signal-to-noise ratio (SNR) is calculated indicating the performance that can be achieved when using the RU. In ONe-PS, the SINR is calculated for each subcarrier and

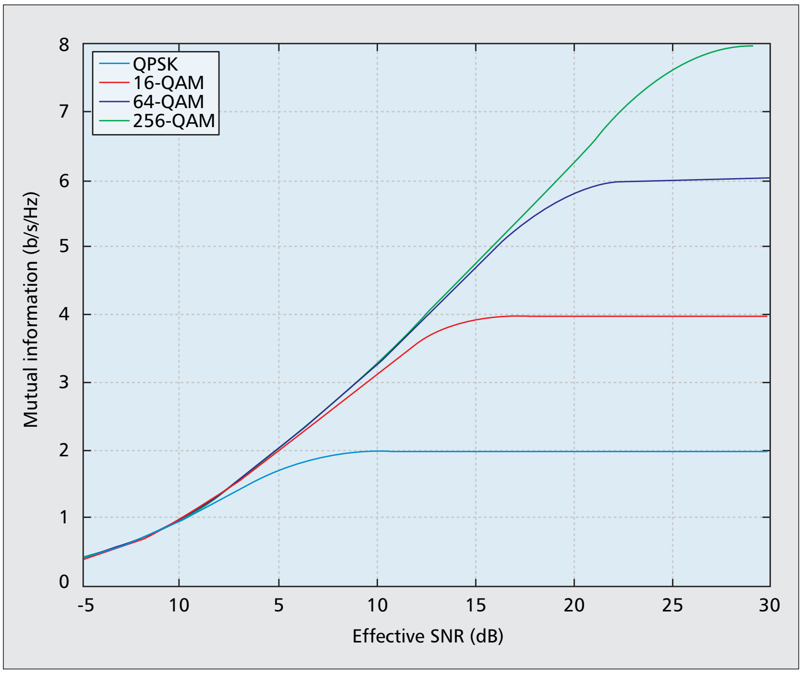


Figure 3. *Average mutual information as a function of the effective SNR.*

OFDM symbol depending on the fading channel coefficients. Instead of calculating the expectation value of the SINR conditions on the subcarriers, the mutual information is calculated for each subcarrier considering the modulation used for the RU. This takes into account that very bad channel conditions have a stronger impact on the performance than very good channel conditions. Afterward, the average mutual information for each RU is derived, and an effective SNR can be given that would lead to the same mutual information for the RU. The relationship between average mutual information and effective SNR can be seen in Fig. 3, showing results obtained from Monte Carlo simulations for different modulation types.

The effective SNR is used as a performance measure during RA and link adaptation in the RRM module. It is used to determine the block error probability (BLEP) of the RU after decoding in the receiver, which is known as effective SNR mapping and is a link to system-level interface that is widely used when evaluating OFDMA systems [10]. BLEPs are obtained from link-level simulations implementing all necessary transmitter and receiver structures of the system.

Evaluation and Performance Results

In this section some performance results are given. The investigated resource allocation strategies described in the following are well known, so only example results are presented in this article. However, it is shown that the proposed SLS concept has no limitations regarding the results that can be achieved compared to dynamic SLSs, which have higher computational complexity. ONe-PS is able to provide results for the SINR experienced by the SS, active session, and cell throughput, as well as the delay, packet error probability, and SS outage. Some example results obtained for a specific scenario showing the impact of data traffic and RA strategies are discussed in the following.

The main system and simulation parameters can be found in Table 1. A cellular wireless system in the downlink is considered. The system does not follow any specific standard, but general conclusions for wireless OFDMA systems can be drawn. Without loss of generality, omnidirectional antennas at BSs and SSs are considered, and the BSs are placed in the center of hexagonal cells. SSs are distributed uniformly in the simulation area and assigned to the BS with the lowest path loss. The amount of users placed in each cell depends on the traffic model. The amount of active users is chosen such that on average, an equal amount of data is offered to each cell for transmission.

The system contains transmit blocks (TBs) of four RUs that are used for transmission of data to the SS. A TB can last one, two, or four RU durations. After each RU duration, two TBs become free for RA. Four different RA strategies are considered in this investigation. The TB can be allocated either randomly (RR), so that the minimum active session throughput in a cell is maximized (MMT), so that the allocated number of RUs is proportionally fair (PF), or so that RUs are allocated to the SS with the best SINR

Parameter	Value
Cellular structure	25 hexagonal cells, frequency reuse of 1, omnidirectional antennas in the cell center, wraparound
Site-to-site distance	1000 m
Path loss exponent	3.5
Standard deviation shadow fading	8 dB
User velocity	8.3 m/s
Channel model	ITU vehicular A channel type
Center frequency	450 MHz
System bandwidth	1.25 MHz
FFT size	128
Subcarrier spacing	11 kHz
Symbol duration including cyclic prefix	100 μs
RU bandwidth	264 kHz
RU duration	1.4 ms
Noise floor	–174 dBm/Hz
Transmit power for traffic channels	41.7 dBm
Modulation	QPSK, 16-QAM, 64-QAM, 256-QAM
Coding	Low density parity check codes, code rate 1/6, 1/3, 1/2, 2/3, 3/4, 5/6
RA aims	Random allocation (RR),proportional fairness in resources (PF), maximizing the minimum SS throughput (MMT), maximizing the sum throughput in the cell (MST)
Service data rate — data traffic combinations	Download and Web browsing with 100 kb/s, download with 1 Mb/s
Average traffic load per snapshot and cell	10 Mbytes
User outage	If active session throughput is less than 10% of service data rate
Snapshot duration	10 s
Number of snapshots	200

Table 1. *Main system and simulation parameters. FFT: fast Fourier transform.*

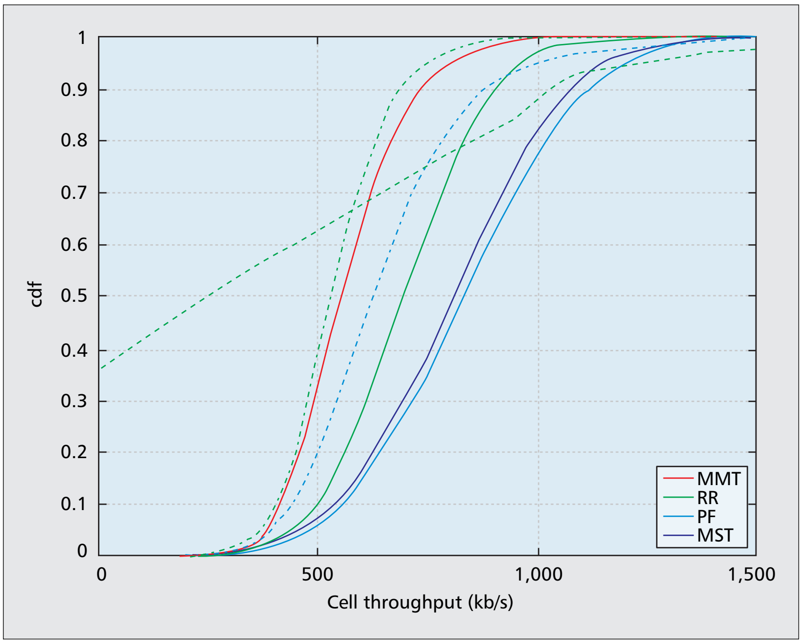
conditions (MST). Other RA strategies are also possible but not considered in this article.

Two different data traffic types, download and Web browsing traffic, are considered in this investigation with different SDRs. For download traffic one file has to be downloaded, while Web browsing traffic consists of packet calls of small size. The packet calls are interrupted by a reading time period where the SS goes idle. A user is considered unsatisfied if the active session throughput is below 10 percent of the SDR. To make the different scenarios comparable, the sum amount of data provided within one snapshot remains constant. The amount of users per cell depends on the amount of data each session contributes in one snapshot.

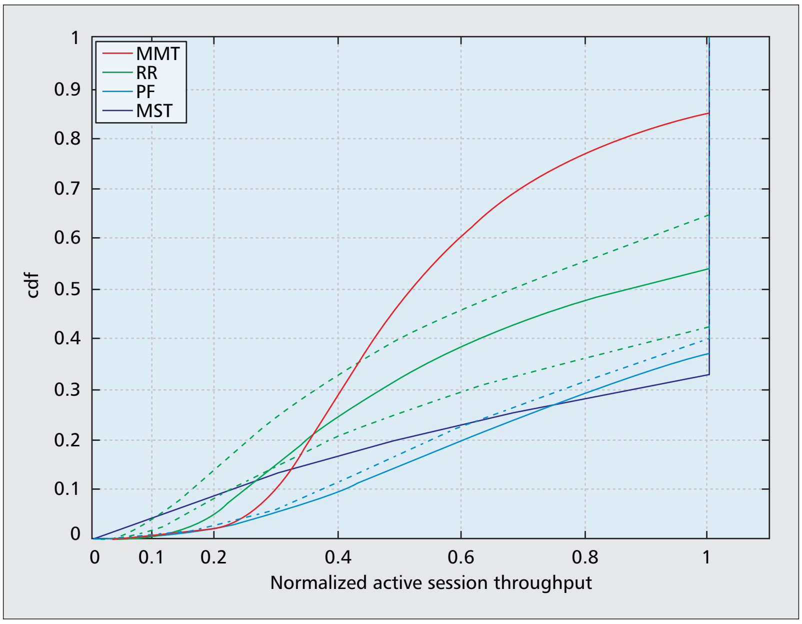
In the following results for the distribution of the cell throughput and the active session throughput normalized to the SDR are presented. Curves of the same color represent the same RA strategy, curves of the same line style represent the same data traffic type and SDR.

Figure 4 shows the cumulative distribution function (cdf) of the throughput measured per cell of the simulation area averaged over one snapshot. The cell throughput in the assumed scenario for download traffic with SDR of 100 kb/s and RR allocation is between 440 and 950 kb/s in 90 percent of the investigated cells. It can be seen that the RA strategy influences the cell throughput distribution. If MST or PF is used, higher cell throughput is achieved than with RR. Both strategies perform equally due to allocating RU only to SSs with the best actual SINR conditions or good actual SINR conditions compared to average SINR conditions. Cell throughput of more than 1 Mb/s can be achieved in approximately 20 percent of the cells. MMT leads to worse cell throughput results, less than 730 kb/s in 90 percent of the cells. Looking at the results for download traffic with 1 Mb/s, it can be seen that 35 percent of the cells do not contain active SSs, and no cell throughput is achieved during the snapshot. On average only one SS is active simultaneously per cell, while in a scenario with an SDR of 100 kb/s, on average 10.6 SSs are active in parallel per cell to provide the same sum amount of data per snapshot. Due to the small number of SSs, all RAs perform equally well for download traffic and an SDR of 1 Mb/s, and only the result for RR is given in Fig. 4. For Web browsing traffic with an SDR of 100 kb/s, a high number of SSs are also active simultaneously, on average 40 per snapshot and cell, but not all of them have data for transmission available due to the reading time period; thus, RUs cannot be utilized and the cell throughput is reduced. Therefore, all RAs perform worse than in the scenario with download traffic due to fewer SSs being available for selection. The reduction for the median cell throughput is 150–200 kb/s for all RA strategies, and the cdfs for RR and PF are given in Fig. 4.

Figure 5 shows the cdf of the active session throughput normalized to the SDR. A normalized active session throughput of 1 means that the active session throughput is equal to the SDR, and all data is transmitted immediately. SSs are in outage if the normalized active session throughput is below 0.1.The cdf of the normalized active session throughput is also a fairness measure: the steeper the cdf, the fairer the system. For download traffic with an SDR of 100 kb/s, it can be seen that only 0.4 percent of the SSs are in outage. Nearly 50 percent of the SSs achieve the SDR as active session throughput. PF and MMT lead to similar results regarding the SS outage, but PF achieves a normalized active session throughput of 1 for over 60 percent of the SSs, while MMT is able to provide maximum normalized active session throughput to only 15 percent of the SSs. MST is more unfair than the other algorithms by privileging



■ **Figure 4.** *Distribution of cell throughput, solid line: download with SDR 100 kb/s, dashed line: download traffic with SDR 1 Mb/s, dash-dotted line: Web browsing with SDR 100 kb/s.*



■ **Figure 5.** *Distribution of normalized active session throughput, solid line: download with SDR 100 kb/s, dashed line: download traffic with SDR 1 Mb/s, dash-dotted line: Web browsing with SDR 100 kb/s.*

The proposed SLS concept is used for modeling and evaluation of OFDMA based systems like WiMAX or LTE. The snapshot based concept has less computational complexity than conventional dynamic SLS and still considers the influence due to data traffic or RRM.

SSs with good SINR conditions so that nearly 4 percent of the SSs are in outage. The best trade-off between fairness and performance is given by PF. If download traffic with SDR of 1 Mb/s is considered, again a high number of SSs are in outage (i.e., 3.6 percent) due to high QoS requirements. Also again, the different RAs perform equally due to a low number of SSs active simultaneously (i.e., on average one SS per cell), and only the results for RR are presented in Fig. 5. Considering Web browsing traffic with an SDR of 100 kb/s, similar outage results can be achieved as for download traffic. A higher number of SSs are active simultaneously per cell, but only a fraction of the SSs have data for transmission and are considered during RA. For RR allocation, a lower number of SSs during RA for Web browsing than for download traffic leads to a higher number of RUs allocated to each single user, so on average a higher normalized active session throughput than for download traffic is achieved, as depicted in Fig. 5. Adaptive RA, like MMT, MST, or PF, performs worse if fewer SSs are available for selection due to lower multiuser diversity. This effect compensates for the higher amount of RUs that can be allocated to each single user, so the normalized throughput is smaller for MMT, MST, and PF for Web browsing than for download traffic. The results for RR and PF are shown in Fig. 5.

Conclusion

A snapshot-based modular SLS concept is presented in this article. The proposed SLS concept is used for modeling and evaluation of OFDMA based systems like WiMAX or LTE. The snapshot based concept has less computational complexity than conventional dynamic SLS and still considers the influence due to data traffic or RRM. Path loss and shadowing remain constant during each snapshot, so a pool of values can be calculated in advance of the simulation run, and combinations are taken randomly from the pool to form independent snapshots with random SS positions. A data traffic model is presented in this article for the proposed concept that cuts out a random interval from the busy hour with SSs that are already active at the beginning of the snapshot, and enter or leave the system during the snapshot. Additionally, a definition of an RU is presented that makes ONe-PS able to model different wireless systems with subcarriers grouped together that may be physically neighbored as well as distributed over the whole system bandwidth. Furthermore, the RU concept introduces flexibility in terms of system bandwidth or frame duration, so the concept is not limited to one specific system design but can be adapted easily to different demands. This is a very important issue because it is expected that future wireless systems will have this flexibility as a requirement. An information theoretic quality measure is proposed for the RU based on the mutual information of each subcarrier that is also used during RA and link adaptation. Some performance results are presented that show the ability of the presented concept to model and evaluate the influence of RRM and data traffic on the user and system performance.

References

[1] A. R. Mishra, *Fundamentals of Cellular Network Planning and Optimisation*, Wiley, 2004.

[2] K. B. Letaief and Y. J. Zhang, "Dynamic Multiuser Resource Allocation and Adaptation for Wireless Systems," *IEEE Wireless*, vol. 13, no. 4, Aug. 2006, pp. 38–47.

[3] A. Fernekeß *et al.*, "Influence of Traffic Models and Scheduling on the System Capacity of Packet-Switched Mobile Radio Networks," *Proc. IST Mobile & Commun. Summit*, Myconos, Greece, June 2006.

[4]D. Soldani, A. Wacker, and K. Sipilä, "An Enhanced Virtual Time Simulator for Studying QoS Provisioning of Multimedia Services in UTRAN," *MMNS*, LNCS 3271, Springer, Dec. 2004, pp. 241–54.

[5] R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, 2000.

[6] J. Zander and S.-L. Kim, *Radio Resource Management for Wireless Networks*, Artech House Publishers, 2001.

[7] T. S. Rappaport, *Wireless Communications Principles and Practice*, Prentice Hall, 2002.

[8] C. F. Ball *et al.*, "Performance Evaluation of IEEE 802.16 WiMAX with Fixed and Mobile Subscribers in Tight Reuse," *Euro. Trans. Telecommun.*, vol. 17, Mar. 2006, pp. 203–18.

[9] A. Fernekeß *et al.*, "Influence of High Priority Users on the System Capacity of Mobile Networks," *Proc. Wireless Commun. Net. Conf.*, Hong Kong, China, Mar. 2007.

[10] E. Tuomaala and H. Wang, "Effective SINR Approach of Link to System Mapping in OFDM/Multi-Carrier Mobile Network," *Proc. Int'l. Conf. Mobile Tech., Apps., and Sys.*, Nov. 2005.

Biographies

ANDREAS FERNEKEß (a.fernekess@nt.tu-darmstadt.de) received his diploma in electrical engineering and information technology with a focus on communications engineering from Technische Universität Darmstadt, Germany, in 2004. Since 2005 he has been pursuing his Ph.D. at the Institute of Telecommunications of Technische Universität Darmstadt as a member of the research group of the Communications Engineering Laboratory. His research interests are in the planning and dimensioning of packet-switched wireless systems, and the impact of data traffic and radio resource management on the system performance.

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