Influence of M2M Communication on the Physical Resource Utilization of LTE

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***Abstract*—The number of Machine-to-Machine (M2M) applications is rapidly increasing in cellular communication systems. In order to ensure a maximum system capacity, the impact of this special kind of traffic on common Human-to-Human (H2H) communication needs to be analyzed. In this paper, a system model for performance evaluation of cellular networks like Long Term Evolution (LTE) in the presence of M2M communication and under different Quality of Service (QoS) constraints is presented. By means of a Markovian model, which is parameterized by laboratory measurements and ray tracing simulations, an estimation of the behavior of LTE for different traffic characteristics is shown. We present blocking probabilities for an LTE network with heterogeneous M2M and H2H traffic and compare different transmission strategies for M2M communication to minimize the impact on human users. The results show that particularly a large number of devices with a low data rate influences the utilization of an LTE cell very negatively.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA)-based cellular communication networks are typically designed for high data rate applications. However, new services in the area of M2M communications are implemented in these systems, like wireless sensor networks. One example is the area of traffic jam prognosis, where devices in cars collect sensor information and transmit them to a server. On the other hand, a download of relevant information from a server, for example the current traffic situation, is needed. The characteristics of M2M communication are quite different to H2H communication. Typically, M2M applications receive or transmit only a small amount of data or require very low data rates. Hence, the impact of small packets transmitted periodically needs to be analyzed.

For the performance evaluation of LTE in this paper a close to reality parameterized Markovian model is used. In Fig. 1 advantages and disadvantages of approaches for modeling wireless communication systems are illustrated. Usually simulations are used to analyze scenarios with a large number of devices, although a lot of effects occurring in a communication system are difficult to model by using this approach. On the other hand, field trials are very complex and often a limited

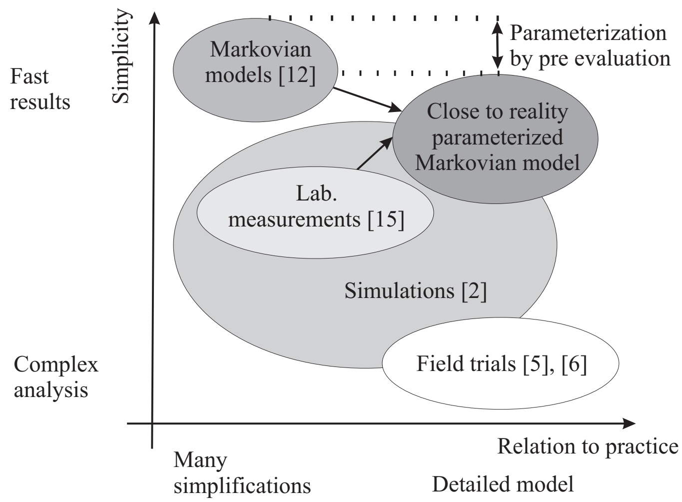

Fig. 1: Approaches to model wireless communication systems

control of the system parameters as well as the environment is given. Therefore, the approach presented in this paper uses measurements with real equipment by extending a common laboratory environment with a fading channel emulator. In this way, the performance evaluation for single users with different requirements regarding the number of Resource Blocks (RBs) is possible. With this measurement setup it is possible to analyze the influence of complex channel models on an End-to-End connection in a laboratory environment. Thereby, the full control of the system parameterization including the fading channel is given.

The results of these laboratory measurements are used to parameterize the Markovian model in order to investigate the influence of many M2M devices with different requirements on the overall cell capacity. The parametrization includes a distribution of the Signal to Noise Ratio (SNR) from ray tracing simulations. The main novelty of this paper is the combination of an analytical Markovian model and laboratory measurements from a standard conform LTE radio link. This makes close-to-reality scalability analyses possible, without deploying a Base Station (BS) and many mobile devices in the field, which would be very cost intensive. With this LTE evaluation system model, the influence of different M2M

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transmission strategies with respect to the usage of a different number of RBs on the QoS of H2H users is evaluated. By means of the results, the maximum number of M2M devices in an LTE cell that can be served without significant influence on the blocking probability for other users is determined. Hereby, the number of shared LTE RBs is the bottleneck in the scenario. Often, the signaling procedure and the random access are critical in M2M scenarios. In our scenario this is not the case, because this become only crucial for thousands of devices in one cell [1].

II. Related Work

Many M2M applications are present in OFDMA-based communication systems. In [2], a suggestion for the resource allocation in a scenario with many M2M devices within 3^{rd} Generation Partnership Project (3GPP) networks can be found. Thereby, the jitter is adopted as main QoS metric. Furthermore, in [3] a study of the impact of mixed traffic on the LTE performance is presented. The authors of [3] focus on different multimedia and Internet applications.

For the performance evaluation of LTE, field trials are often used in order to analyze the impact of velocity on the performance of OFDMA based links. For example the performance of LTE is evaluated by a testbed in [4]. For throughput measurements, a monitoring car with an average speed of around 30 km/h is used. Hereby, it is very difficult to get reproducible results. Hence, real world measurements often consider static scenarios [5] or scenarios with low velocity ([6]; pedestrian 3 km/h fading channels in downlink and static channels in uplink).

Ray tracing simulations are a well known method for evaluating channel conditions for cellular networks. In [7] the coverage and achievable peak data rates for an urban area are investigated within a ray tracing simulation for an LTE-Advanced relay scenario.

In [8] and [9], Markovian models are used to analyze LTE networks. Thereby, different channel conditions are modeled by different states. A Markovian model for resource allocation, where one state represents a part of the shared resources, can be found in [11]. In [12] a multiclass Erlang loss model is introduced for OFDM systems. Every state in the model represents one subcarrier. We adopted the model in order to make it more practice-oriented for LTE systems by using the RBs as states. Furthermore, this model is parameterized by measurements and ray tracing simulations.

III. System Model

In order to evaluate the performance of LTE, the presented system model consists of a laboratory setup (LTE base station emulator (BSE), channel emulator for fast fading and User Equipment (UE)), ray tracing simulations and a Markovian model are used (cf. Fig. 2). Hereby, a typical urban outdoor scenario (Vehicular A channel model defined by the ITU [13]) is assumed. For this scenario, we measured User Datagram Protocol (UDP) downlink data rates for single users as a function of the SNR and the number of allocated RBs per user. One RB is the smallest unit, which can be allocated to one LTE user. The distribution of the SNR within the urban outdoor scenario is determined by the ray tracing simulation.

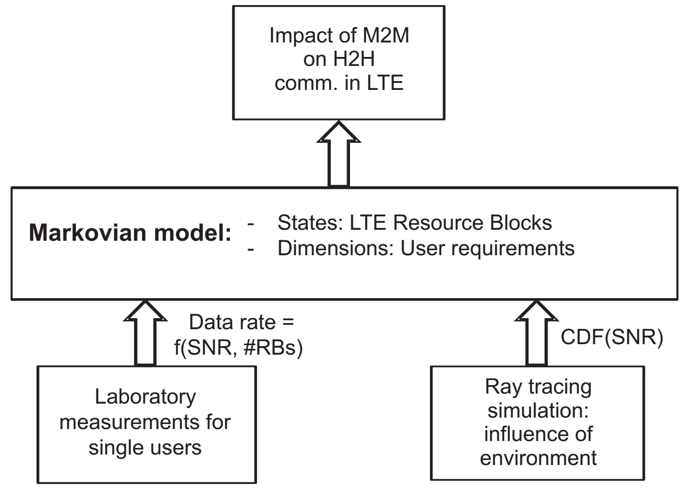


Fig. 2: LTE system capacity model for the utilization of the LTE radio interface

The behavior for many users in an LTE cell is analyzed by a Markovian model. Assigning the user requests to different classes of resources, each class is modeled by one dimension in the Markovian model. According to the reduction of dimensions of Markovian models [14], an LTE cell with different user QoS requirements and various SNRs is modeled.

The users are divided by their requirements (H2H with a data rate of 1 Mbit/s; M2M with 10 kByte UDP data) and their SNR. By means of the Markovian model, the blocking probability of H2H communication and the traffic load is evaluated for different user behaviors and transmission strategies in terms of the assignment of a different number of RBs.

In the following the individual parts of the framework are described in more detail:

A. Laboratory Measurement Setup

Instead of performing measurements in a field trial, we use an approach based on radio channel emulation (cf. [15]). The setup (for parameters see Tab. I) enables measurements of typical Key Performance Indicators (KPI) at the application layer. In the following, the different elements of the measurement setup are described:

- The creation of a mobile network cell in a laboratory environment allows a *Base Station Emulator (BSE)*. This hardware makes a detailed parameterization of the LTE base station signal in terms of modulation and coding scheme, transmit power, (Hybrid) Automatic Repeat Request ((H)ARQ) and number and position of allocated RBs possible.
- The RF signal provided by the BSE serves as input for the downlink channel of the *channel emulator* (circulators are used at the bidirectional ports for a separation of the

signal components). The channel emulator afterwards manipulates the signal in a predefined manner. This includes fast fading due to mobility in the scenario. Moreover, noise (Additive White Gaussian Noise (AWGN)) is added to the RF signal. For the emulation of the mobile radio channel the ITU Vehicular A channel model [13] is used.

- The *User Equipment (UE)* is remote controlled by a client PC via USB. We establish a standard conform radio connection between the BSE and the UE (Samsung GT B3730).
- For *application testing* iPerf [16] is executed on a server. This allows for End-to-End testing between the server and the connected client. We measured the UDP downlink data rates for single users in an LTE cell as a function of the number of allocated RBs.

B. SNR Analysis by Ray Tracing Simulations

In order to analyze the SNR estimation for realistic large-scale topologies, an urban outdoor scenario representing the inner city of Paris has been modeled for 3D ray tracing. Besides realistic assignment of material properties for the surrounding area and buildings, the simulation also takes into account multi-path propagation, caused by reflection, diffraction and scattering at outer building walls. The parameters for the simulation are shown in Tab. I, whereas the receiver UE height is set to 1.5 m and the base station height is set to 30 m. For evaluation purpose, a single base station with three sectors using different frequencies from LTE band 7 (reuse 3) is deployed in the scenario. The first antenna (Ant. 1) uses 2.62 GHz as center frequency, Ant. 2 and Ant. 3 use 2.63 GHz, respectively 2.64 GHz as center frequency. Fig. 3 shows the overall received power for the described scenario using Ant. 2 for a range from -50 dBm to -130 dBm.

C. Analytical Markovian Model

By means of the Markovian model the different resource requirements of users are modeled in an analytic way. Assuming that the appearance and duration of customer service requests follow a negative exponential distribution with respect to time, an analytical Markovian model can be developed. Assigning the user requests to different classes of resources, each class is modeled by one dimension in the Markovian model. According to the reduction of dimensions [14], an LTE cell with different QoS requirements and different channel conditions regarding the SNR can be modeled as shown in Fig. 4. Thereby, the j^{th} state denotes the allocation of j RBs from the LTE OFDMA downlink signal. Moreover λ_s and μ_s denote the mean arrival and mean service rate of the s^{th} class. As an example Fig. 4 shows three service classes. Class 1 allocates one RB, class 2 two RBs and class 3 allocates $k-1$ RBs.

TABLE I: LTE system parametrization

Measurement parameter	**Value**
Carrier frequency	LTE band 7
Channel bandwidth	10 MHz (50 RBs)
Fast Fourier Transform size	1024
Modulation schemes	QPSK, 16 QAM, 64 QAM
Coding rates	1/2, 3/4
Duplexing scheme	Frequency Division Duplexing
SNR	0-30 dB
UE category	3
RLC ARQ mode	Acknowledged mode
Ray tracing parameter	**Value**
Ray tracing model	3D Intelligent Ray Tracing [10]
Transmit power	40 dBm
BS antenna gain	16.7 dBi
BS antenna opening angle	120°
UE antenna gain	1 dBi
UE noise figure	6 dB
Downtilt	3°
Cell radius	1 km
Noise	Thermal noise

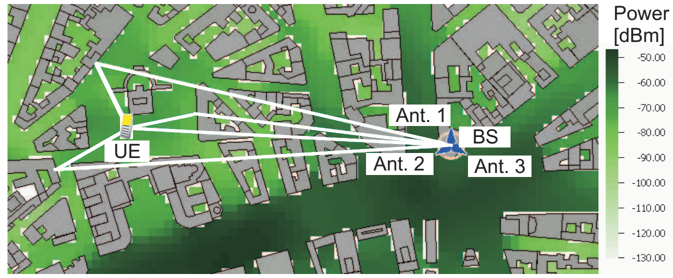


Fig. 3: Example for multi-path propagation in an urban environment for Ant. 2

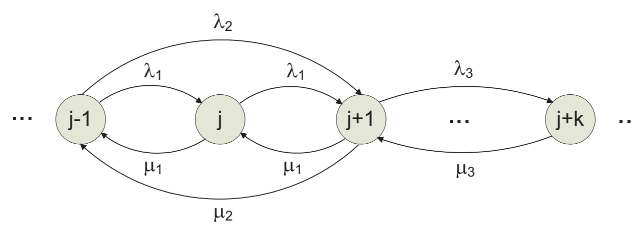


Fig. 4: Exemplary one-dimensional Markovian model

According to [14] the stationary distribution π_c, which characterizes the probability that c RBs are allocated, can be determined in a recursive way

$$\pi_c = \frac{\widetilde{\pi}_c}{\sum\limits_{c=0}^{C} \widetilde{\pi}_c} \quad \text{with} \quad \widetilde{\pi}_c = \begin{cases} 1 & c = 0 \\ \sum\limits_{s=1}^{S} \frac{a_s c_s}{c} \widetilde{\pi}_{c-c_s} & c > 0 \,, \end{cases}$$

where C is the overall number of RBs, a_s the offered traffic of class s, c_s the corresponding resources of class s and S the number of service classes, i.e. dimension of the model. The blocking probability p_{b_s} of class s and the overall traffic load Y can be calculated as

$$p_{b_s} = \sum_{c=C-c_s+1}^{C} \pi_c \quad \text{and} \quad Y = \sum_{c=1}^{C} c\pi_c \,.$$

The model realizes a First In First Out (FIFO) scheduling algorithm. If the required number of RBs allocated by the UE is available in the cell, the UE will get the requested resources.

If the number of free RBs is smaller than the requested number of RBs, the request from the UE will be rejected. Hence, all devices (H2H and M2M) have the same priority.

For the presented results we use six different classes (according the nomenclature of the arrival rates):

- H2H; good SNR ($a_{H,1}$)
- H2H; medium SNR ($a_{H,2}$)
- H2H; bad SNR ($a_{H,3}$)
- M2M; good SNR ($a_{M,1}$)
- M2M; medium SNR ($a_{M,2}$)
- M2M; bad SNR ($a_{M,3}$)

The arrival rate of all H2H users ($a_H = a_{H,1} + a_{H,2} + a_{H,3}$) is denoted as a_H and we use a_M for the arrival rate of all M2M users. For λ_s and μ_s the same indices are used. The service rate for the H2H users is set to 1 per second and the offered traffic is adjusted by the corresponding arrival rate. For M2M users, the service rate is derived from the data rate taken from the laboratory measurements divided by the payload size of 10 kByte.

IV. Results

In the following, the results corresponding to the different parts of the previously described system model are presented. This includes the derivation of the velocity and SNR depended data rate based on laboratory measurements as well as the SNR analysis by ray tracing simulations. Finally, the blocking probability is presented based on a close to reality parameterized Markovian model.

A. Laboratory Measurements

The UDP downlink data rates dependent on the SNR for 50 Resource Blocks per user compared to 1 RB per user can be seen in Fig. 5 and Fig. 6. for different Modulation and Coding Schemes (MCS). For an SNR of 20 dB a data rate of 19.5 Mbit/s for a 64 QAM with a code rate of R = 1/2 and a velocity of 120 km/h can be achieved. This relates to a data rate of 0.39 Mbit/s per allocated RB. If one user allocates only 1 RB the data rate is reduced to 0.30 MBit/s (cf. Fig. 6). Thereby, we identified that the position in the spectrum has no influence on the data rate.

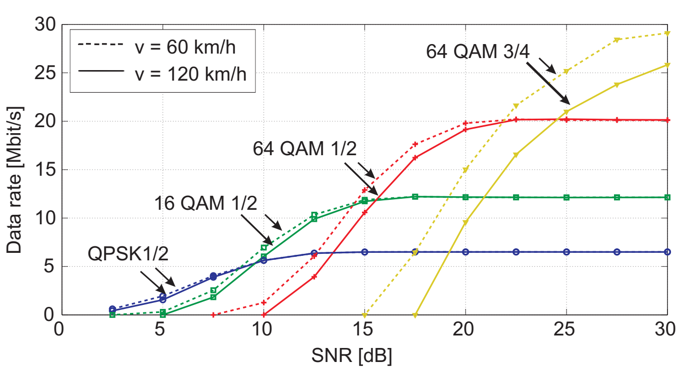


Fig. 5: Laboratory measurements: Downlink data rate vs. SNR for 50 RBs per user

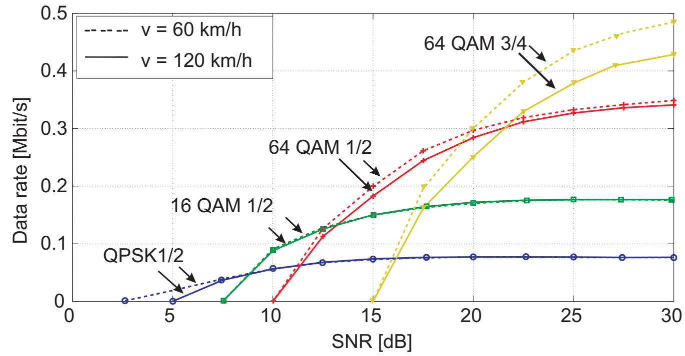


Fig. 6: Laboratory measurements: Downlink data rate vs. SNR for 1 RB per user

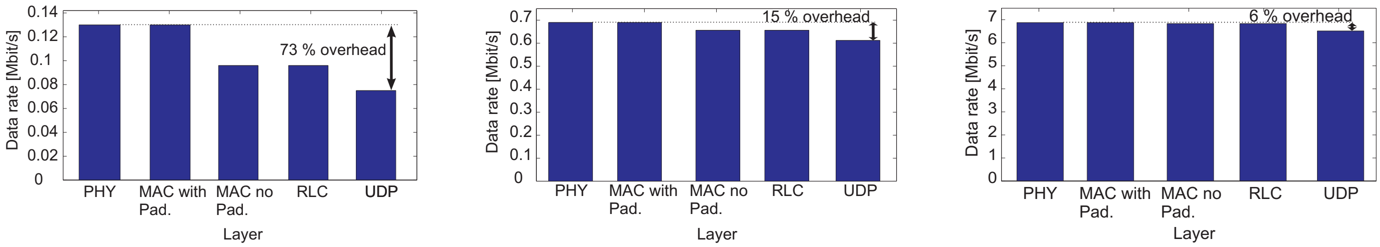
The main reason for different data rates per RB is the high overhead between physical layer (PHY) and transport layer (UDP) for low data rates, because the Media Access Control (MAC) padding and the Protocol Data Unit (PDU) size in the Radio Link Control (RLC) layer is depending on the incoming data rate. Therefore, the overhead (cf. Fig. 7) for low data rates (1 RB; 73 % between PHY and UDP) is significantly higher than for high data rates (50 RBs; 6 % between PHY and UDP). This means, the UDP capacity for the OFDMA signal is higher if the whole spectrum (50 RBs) is allocated to one user instead of 50 users allocate 1 RB each. Therefore, we measured the data rates for all possible numbers of RBs per user and used these results for parameterizing the Markovian model. We identified that the impact of the SNR on the data rate is much stronger than the impact of the velocity (cf. Fig. 5). Hence, we differentiated the users only by the SNR. The received signal quality of the UEs is divided into three parts:

- SNR $\leq$ 15 dB: represented by 10 dB SNR
- 15 dB $<$ SNR $\leq$ 25 dB: represented by 20 dB SNR
- 25 dB $<$ SNR: represented by 30 dB SNR

B. SNR Estimation by Ray Tracing Simulations

We have shown that the available data rate is strongly influenced by the channel quality between base station and UE (cf. Fig. 5 and Fig. 6). Hence, the number of required RBs for H2H services with a fixed data rate depends on the channel quality. For a video streaming service with 1 Mbit/s 9, 3 or 2 RBs are needed if the SNR is equal to 10 dB, 20 dB or 30 dB (cf. Tab. II). For M2M users a download of 10 kByte is assumed. In the following, we compare different transmission strategies for M2M communications regarding a different number of RBs allocated by M2M users. 1 ($M2M_1$), 5 (class $M2M_5$) or 10 (class $M2M_{10}$) RBs are statically allocated for M2M users. Hence, the service rates are different for varying numbers of RBs, because the time for the download of the payload is different (cf. Tab. II). The number of required RBs for different user classes and the resulting M2M service rates can be found in Tab. II and Tab. III.

We assume that the users are homogeneously distributed in an urban scenario. Within the ray tracing simulation two urban scenarios are used, one with a high building density



(a) 1 RB per user (b) 5 RBs per user (c) 50 RBs per user

Fig. 7: Lab. measurements: Downlink data rate on different layers for a varying number of RBs; QPSK, MCS = 8 and $R = \frac{1}{2}$

TABLE II: Number of RBs for different user classes; Video: 1 Mbit/s; M2M: 10 kByte

	H2H	$M2M_1$	$M2M_5$	$M2M_{10}$
Far; SNR $\leq$ 15 dB	9	1	5	10
Mid; 15 $<$ SNR $\leq$ 25 dB	3	1	5	10
Near; SNR $>$ 25 dB	2	1	5	10

TABLE III: Service rate for different user classes; Video: 1 Mbit/s; M2M: 10 kByte

	H2H	$M2M_1$	$M2M_5$	$M2M_{10}$
Far; SNR $\leq$ 15 dB	1 / s	1.1 / s	8.25 / s	18.5 / s
Mid; 15 $<$ SNR $\leq$ 25 dB	1 / s	3.55 / s	20.4 / s	50.3 / s
Near; SNR $>$ 25 dB	1 / s	5.36 / s	32.9 / s	62.7 / s

and one with a low building density. The exemplary map of the SNR distribution of the scenario with a high building density is illustrated in Fig. 8. In Fig. 9 the corresponding Cumulative Distribution Functions (CDFs) of the SNR for both scenarios are shown. The probability for an SNR below 15 dB is 26 %, for an SNR between 15 dB and 25 dB is 37 % and for an SNR higher than 25 dB is 37 % (for high building density). All users are partitioned by these fractions. Therefore, 26 % of all H2H users have an SNR smaller than 15 dB ($0.26 \cdot a_H = a_{H,1}$).

C. Markovian Model

In Fig. 10 the blocking probability of H2H as a function of the arrival rate of M2M devices λ_M for a different number of RBs per user is shown. Hereby, an arrival rate for the video class of $a_H = 3/s$ and a payload size of 10 kByte per M2M user is used. Hence, all curves corresponding to the same building density have the same y-intercept. For higher building density the fraction of users with bad channel conditions is higher (cf. Fig. 9). Therefore, the blocking probability for the same arrival rate is higher, too. For a small arrival rate of M2M users the video users are dominant. If the M2M devices transmit with 1 RB, the relative overhead between PHY data rate and UDP data rate is much higher than for 5 or 10 RBs per user (cf. Fig. 7). Hence, the blocking probability with 1 RB is higher than for 5 or 10 RBs per user. For a low building density and an arrival rate of M2M users λ_s of 73 per second and a transmission with 10 RBs, the blocking probability for the video class is 10 %. In contrast to that, the blocking

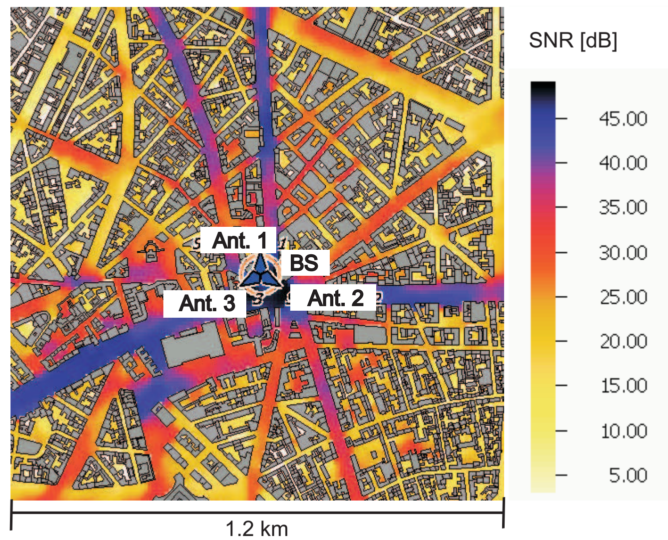


Fig. 8: Ray tracing: Map for the SNR in an urban environment with high building density

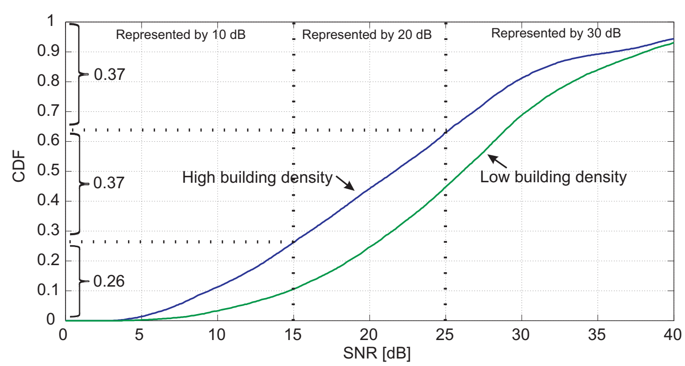


Fig. 9: Ray tracing: CDF of the SNR in an urban environment

probability of the video class is 33 % if only 1 RB is used for the M2M class. Or rather, if the blocking probability should be smaller than 10 % (for QoS requirements) on average 43 M2M devices can be served per second if they transmit with 1 RB while on average 73 M2M devices can be served per second if they transmit with 10 RBs per user. This is an enhancement of 70 % while guaranteeing the same QoS.

The traffic load, respectively the average number of used RBs for a different number of allocated RBs per user is

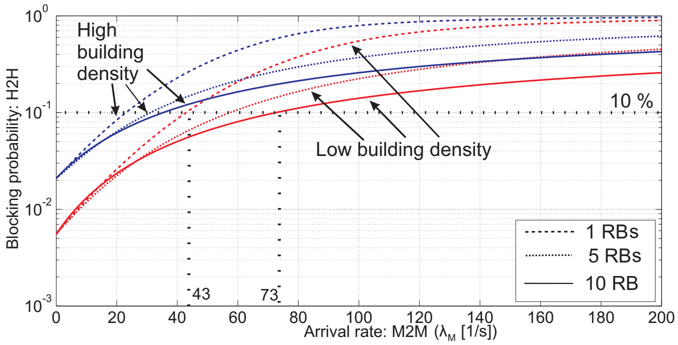


Fig. 10: Markovian model: Blocking probability vs. arrival rate of M2M devices for a different number of RBs per user

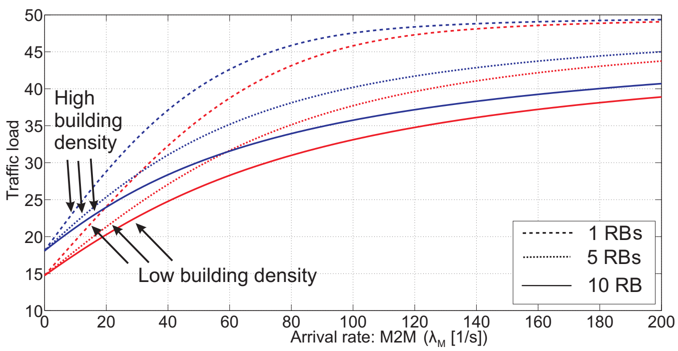


Fig. 11: Markovian model: Traffic load vs. arrival rate of M2M devices for a different number of RBs

illustrated in Fig. 11. We see that a transmission with 1 RB stresses the LTE cell much more than a transmission with 10 RB. For a low building density, an arrival rate of M2M users $\lambda_s = 100/s$ and a transmission with 10 RBs, on average 17 RBs are unused in the cell. In contrast to that, only 4 RBs are available with an allocation of 1 RB per user. Thereby, the same UDP payload (10 kByte per user) is transmitted.

V. Conclusion and Future Work

In this paper, we have presented an efficient system model for the performance evaluation of LTE with realistic channel conditions in the presence of H2H as well as M2M communications. Thereby, a Markovian model parameterized by laboratory measurements and ray tracing simulations is used. By means of the framework, different transmission schemes regarding the resource allocation of M2M users were compared. The model shows that due to different overheads, the data rate per RB is strongly dependent on the number of allocated RBs per user. Hence, the blocking probability for an LTE cell with many users, which transmit with a low number of RBs, is high. For a QoS requirement of 10 % blocking probability, 43 M2M devices can be served per second if they transmit with 1 RB. In contrast 73 M2M devices (enhancement of 70 %) can be served per second if they transmit with 10 RBs, although the same average UDP data rate for all users is reached.

In the next step, we will use a scenario with complex network topology and investigate the influence of interferences in the laboratory and for the ray tracing simulation. Furthermore, we will validate the results with a protocol simulation.

Acknowledgment

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