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Performance of Channel-Aware M2M Communications based on LTE Network Measurements

Christoph Ide, Bjoern Dusza and Christian Wietfeld
Communication Networks Institute
TU Dortmund University
44227 Dortmund, Germany
e-mail: {Christoph.Ide, Bjoern.Dusza, Christian.Wietfeld}@tu-dortmund.de

***Abstract*—The interaction between Machine-to-Machine (M2M) Communications, also known as Machine-Type Communications (MTC), and Human-to-Human (H2H) Communications is a recent topic in the context of cellular networks like Long Term Evolution (LTE). In this paper, we evaluate the performance of Channel-Aware MTC (CAT) based on LTE resource allocation measurements of a real LTE deployment. By means of a novel measurement setup, which uses a real-time spectrum analyzer, the LTE resource utilization in terms of occupied Resource Blocks (RBs) of the uplink is quantified for different channel conditions. Furthermore, the resource distribution in time and frequency domain, which is determined by the scheduler, is analyzed in this paper allowing for the calculation of average data rates and the spectral efficiency. The measurement results are used to quantize the potential gain of CAT. It is shown that by means of the scheme, the influence of MTC on other LTE users can be significantly reduced. In addition, the fraction of available RBs can be increased by 47%.**

I. INTRODUCTION

For Machine-Type Communication (MTC) applications [1] the influence of the generated traffic on the LTE network and therefore on other users is of special interest. These services should have only a minor or even no impact on the quality of user centric services which are also served by the LTE network [2]. In order to minimize the impact of MTC on Human-to-Human (H2H) communications, we presented Channel-Aware MTC (CAT) in [3]. This scheme bases on the idea that data should be transmitted with a higher probability in case of good channel conditions. However, the conclusions presented in [3] are based on laboratory measurements. Compared to that, the contribution of this paper is an in depth investigation of the impact of different channel conditions on the radio resource utilization in a real LTE network. This paper therefore provides a significant validation of the results presented in [3].

The channel quality has a major impact on the performance of cellular wireless communication systems like Long Term Evolution (LTE). This is due to two main concepts: The channel-aware choice of the Modulation and Coding Scheme (MCS) [4] and the retransmission of erroneously received packets. As each MCS has a different spectral efficiency, the capacity of the overall system is strongly related to radio channel conditions of the active users. This effect is furthermore strengthened by the Automatic Repeat reQuest (ARQ) mechanism that is used on the Radio Link Control (RLC) layer and by the Hybrid Automatic Repeat reQuest (HARQ) that is implemented on the Medium Access Control (MAC) layer [4] in LTE. This leads to the fact that the number of required retransmissions depends on the channel quality [5]. To exemplify these effects, the impact of the radio channel on the achievable throughput is shown in Fig. 1 for different transport layer protocols and different fading conditions. These measurements are performed in the laboratory by means of an LTE base station emulation and a channel emulator. More details about the measurement setup can be found in [6]. The figure also illustrates the idea of CAT. For good channel conditions (see Ray Tracing map) MTC data should be transmitted with a higher probability in contrast to bad channel conditions.

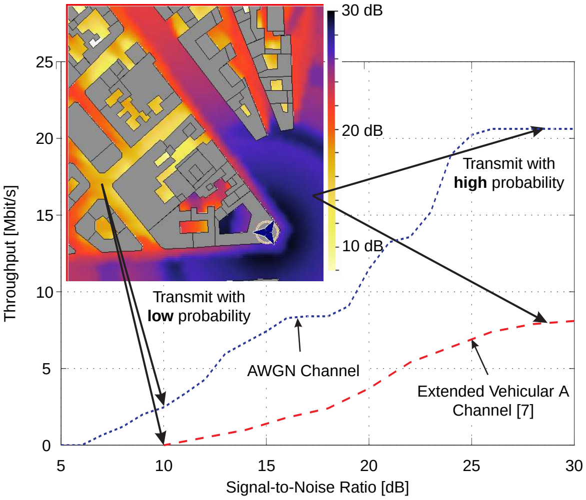

Fig. 1: Radio Channel Dependent UDP Throughput Assuming an Optimum MCS Choice (Laboratory Measurements) and Example Ray Tracing Simulation Illustrating the Idea of CAT.

However, the influence of different channel conditions on the LTE performance (for example its data rate (cf. Fig. 1) or delay) is typically evaluated at the User Equipment (UE). In contrast to this, in this paper we present network-based performance measurements. By means of an innovative measurement setup, the LTE uplink resource utilization is quantified as a function of the channel quality. For this purpose, a real-time spectrum analyzer is used. By means of the measured resource utilization in time and frequency domain, the average

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data rate and the spectral efficiency is calculated. On the UE side, it is not possible to measure the spectral efficiency accurately, because the occupied bandwidth in terms of RBs is not accessible from the LTE chipset. However, by means of our measurement approach not only the Quality of Service (QoS) of one user can be evaluated but also the influence of the generated traffic on a real LTE network and therefore on other users.

The paper is organized as follows: In Section II the related work of LTE performance measurements is presented. The measurement overview with scenario description and measurements setup is illustrated in Section III. The results regarding resource utilization of an public LTE network and the resulting gain of CAT are shown in Section IV. Section V concludes this work.

II. RELATED WORK

The performance of cellular communication systems is often evaluated in dedicated research networks or public networks. Test networks have the benefit that one has full control of the network, including the traffic of all users in the cell. In [8], LTE field measurements in a test network are performed. The authors evaluated for example the cell downlink throughput for one or two users in the cell. Such measurements are performed in many cases by network infrastructure manufacturers and operators [9]. In [10], LTE Multiple-Input and Multiple-Output (MIMO) data rates are presented that were derived by using a measurement van. Thereby, the influence of different antenna configurations is evaluated. The MIMO throughput of an LTE-based 100 MHz testbed under user mobility is shown in [11]. However, public networks are characterized by the additional influence of others, unknown users which are also occupying network resources. On the other hand, the actual user experience can be measured. In [12] and [13], the correlation between the LTE performance and different channel quality indicators (for example Received Signal Strength Indication (RSSI), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and Block Error Rate (BLER)) is evaluated.

Most of the results presented in literature concentrate on UE-based performance evaluation. For example the data rate, delays, Bit Error Rate (BER) or BLER are measured under different channel conditions, mostly for the downlink. Thereby, the Quality of Service (QoS) of the user for which the measurements are performed, is evaluated. Compared to that, the aim of this paper is to present network centric performance measurements of a public LTE system. This allows for the quantification of the required network resources for different channel conditions.

Channel-dependent scheduling is a well-known method to improve the performance of multi-user systems. Typically, these algorithms are applied to the downlink [14]. Scenarios for the uplink were published in [15] and [16]. All these algorithms work in the MAC layer and do not take application requirements into account. Furthermore, these approaches are typically centralized. This means that the base station collects the channel information from all UEs before the scheduling decision is done in the eNodeB. In contrast to that, for the CAT scheme, the transmission decision is done at the UE.

TABLE I: LTE System and Application Parameters.

Measurement parameter	**Value**
Carrier frequency	1.72 GHz
Channel bandwidth	20 MHz
Max. # of RBs in frequency domain	100
RB duration	0.5 ms
RB bandwidth	180 kHz
Duplexing scheme	Frequency Division Duplexing
UE type	Samsung Galaxy S3
Payload size	50 - 400 kByte
Markovian Parameter for [3]	**Value**
Channel environment	Urban
#RBs for MTC traffic	10
MTC payload	100 kByte
H2H data rate	1 Mbit/s
H2H arrival rate	1/10 s
H2H service rate	1/80 s
Coefficient α	5

III. MEASUREMENT OVERVIEW

In this section, the methodology for capturing the uplink scheduling decisions will be described. This includes the explanation of the reference cell scenario as well as an in depth description of the measurement campaign and data processing.

A. Scenario Description

As example scenario a suburban LTE radio cell at the campus of TU Dortmund University in Germany is chosen. The cell is operated by *Deutsche Telekom* at LTE Band 3 and has an overall bandwidth of 20 MHz, i.e. 100 overall available RBs in the frequency domain. Additional parameter of importance are given in Table I. The impact of the radio channel conditions on the RB requirement for the transmission of a fixed sized file has been measured at seven different locations in two different buildings. The measurement points have been chosen in a way that they represent a wide range of channel quality conditions in terms of the RSRP. Table II provides additional information on the respective measurement positions.

The measurement points given in the table are characterized by their position dependent RSRP and RSRQ values. The Channel Quality Indicator (CQI) is not available at the UE that we used. We assume that bad uplink channel conditions, leading to a robust MCS, are reflected by a low downlink RSRP value (due to reciprocity of the radio channel [17]).

TABLE II: Measurement Point Description.

Point No.	**RSRP [dBm]**	**RSRQ [dB]**	**Comments**
1	-105	-8	Room without window
2	-102	-8	4 m from Window, NLOS
3	-100	-8	2 m from Window, NLOS
4	-97	-7	1 m from Window, NLOS
5	-95	-7	At the Window, NLOS
6	-92	-7	At the Window, NLOS
7	-90	-7	Outside, NLOS

In the results section the correlation between uplink resource allocation and downlink channel quality (RSRP) is analyzed.

B. Measurement Setup

For sake of reproducibility, the UE is mounted on top of a tripod that is positioned at a fixed location relative to the antenna. For capturing the radio resource requirement on an LTE UE in a real-world LTE deployment, a real-time spectrum analyzer (Rohde & Schwarz FSVR) is used. This device allows for extremely fast sweeps through the spectrum and therefore for the identification of spectral power even for extremely time variant allocations. For the measurements presented in the following section, a sweep time of 500 μs is applied. The spectrum analyzer is connected to an antenna that captures the uplink transmission signal going from the UE to the eNodeB on top of a neighboring building. For the actual measurements, a User Datagram Protocol (UDP) based file transfer is initiated by proprietary test software. Fig. 2 illustrates the overall setup.

The output of the spectrum analyzer is a raw file format consisting of received power values in a time frequency grid. The left picture in Fig. 3 illustrates such a raw matrix as heat-map, meaning that high received power values are represented by red colors and low transmission power by blue colors. In the first post-processing step, a threshold is applied that allows for the binary differentiation between occupied and free time slots. For our controlled measurement setup with a fixed distance between the antenna and the UE (cf. Fig. 2), a threshold of -47 dBm was found to be a suitable choice. The second picture in Fig. 3 shows the output of this discretization. The figure shows all the resources that are occupied by the UE under test in the time frequency grid. However, this includes not only the Physical Uplink Shared Channel (PUSCH) resources but also the Sounding Reference Signals (SRS) that are requested by the eNodeB for radio channel measurements on currently not assigned RBs. For the determination of the resource requirements of the PUSCH, these signals need to be filtered. The right picture in Fig. 3 shows the result of this proceeding. Beyond this, the x-axis is scaled to represent the resource allocation in terms of actual RBs. Based on this representation of the measurement results, it is now possible to count the actual number of RBs that have been assigned for data transmission.

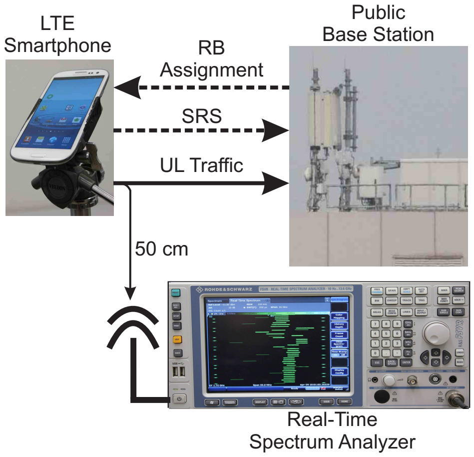

Fig. 2: Measurement Setup for Real-Time Resource Allocation Capturing.

The system performance at the different measurement points (cf. Table II) is evaluated by means of the following metrics:

1) The **total number of RBs** M_Σ that is directly counted as described in the previous paragraph,
2) the **overall transmission time** T that is directly measured as the time between the transmission start and its end,
3) the **average number of RBs** $\bar{M}$ over time that is calculated as $\bar{M} = M_\Sigma / T$
4) the **data rate** DR that is defined as $DR = D/T$ with the data size D,
5) the **spectral efficiency** η of the system that is calculated as $\eta = D[bit]/(M_\Sigma \cdot 180[kHz] \cdot 0.5[ms])$.

For a statistical evaluation, 20 independent measurements have been performed at each of the single measurement locations given in Table II.

IV. Results

In this section, the results of resource requirement measurements are presented first. Then these results are used to evaluate the gain of channel-aware MTC.

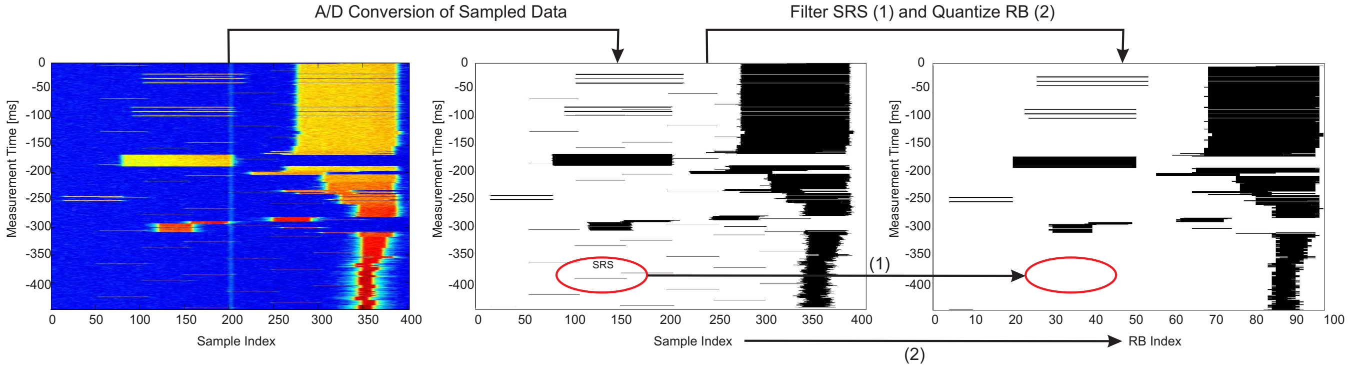

Fig. 3: Post-Processing Chain for Recorded Measurement Data.

A. LTE Resource Utilization Measurements

Quantifying the utilization of the LTE radio interface is of special interest for challenging channel conditions. Therefore, we selected seven different locations with RSRP values between -105 dBm and -90 dBm (cf. Table II). In Fig. 4, the number of allocated RBs is illustrated over time for different RSRP values. It can be seen from the figure that the transmission is completed much faster in case of good channel conditions. This is due to the lower number of total RBs that are required to transmit the data (cf. Fig. 4) and due to the higher average number of allocated RBs. For a low RSRP, the eNodeB assigns a much lower number of RBs to the UE, especially at the beginning of the data transmission.

This effect becomes clearer by having a look on the statistical analysis of the average number of allocated RBs over all transmission (cf. Fig. 5). For bad channel conditions (RSRP = -105 dBm), only 14 RBs median are assigned to the user. The value increases to 40 RBs for a good RSRP of -90 dBm. This effect is unexpected, because the scheduler typically assumed in literature usually apply a resource or rate fair scheduling. For a rate fair scheduling, users with good channel conditions would get even a lower number of RBs in contrast to cell edge users with worse conditions. However, the opposite is obviously done in the real LTE network for a small payload size (100 kByte). It can be measured that for a low RSRP, the number of RBs increases very slowly over time (cf. Fig 4). This leads to a lower average number of RBs for a low RSRP. For a higher RSRP, the number of allocated RBs increases much faster over time. Moreover, for larger payloads, the average number of RBs is much higher (cf. Fig. 5).

The total number of allocated RBs for different RSRP values is shown in Fig. 6. This figure of merit describes how intensive the LTE air interface is utilized by the data transmission. It can be seen that the total RB utilization differs by a factor of four between the best and worst case that we measured. For example for a M2M application, which should interfere as low as possible which other services, this means that the same payload can be transmitted by using only one quarter of resources.

In Fig. 6, also the transmission time is plotted for different channel conditions. Here, a very clear relationship can be observed. For -105 dBm, the average transmission duration is very high (670 ms) due to the low spectral efficiency and the lower average number of RBs. A much faster transmission is possible for -90 dBm (median: 58 ms). The transmission time directly corresponds to the average data rate. The average data rates seem very low for an LTE system, but we have to keep in mind that these are uplink measurements and there is no MIMO available in the uplink in LTE and that the users transmit in many cases only in a very limited part of the spectrum (cf. Fig. 5).

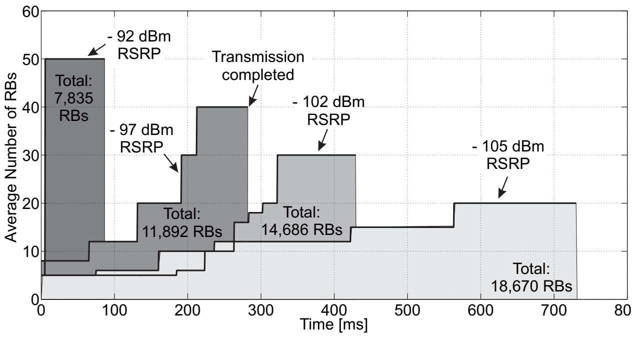

Fig. 4: Number of Allocated RBs vs. Time for Different RSRP Values of Example Transmissions (100 kByte Payload).

The stochastic variations of the measurements are due to uncontrollable effects of the public communication system. These are interferences from users in other cells, varying fast fading due to moving objects between UE and base station (both can result in more retransmissions and therefore a higher number of total allocated RBs respectively a lower spectral efficiency (cf. Fig. 6)) or other users in the same cell (influencing the average number of RBs (cf. Fig. 5)).

B. Performance Evaluation of Channel-Aware MTC

The resource utilization measurement results are used to determine the benefits of a channel-aware MTC data transmission scheme presented in [3]. For this purpose, the Markovian model for resource utilization modeling of LTE for many users (cf. [3]), is parameterized by the results of required RBs from Section IV-A (for further parameters see Table I). Thereby, an eNodeB noise figure of 5 dB is assumed. By means of the model, the blocking probability of H2H traffic (cf. Fig. 7)

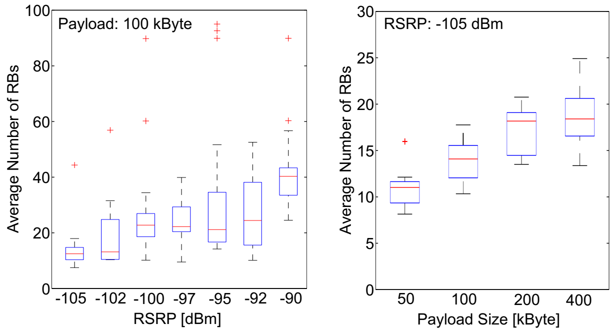

Fig. 5: Average Number of Allocated RBs for Different RSRP Values and Different Payload Sizes.

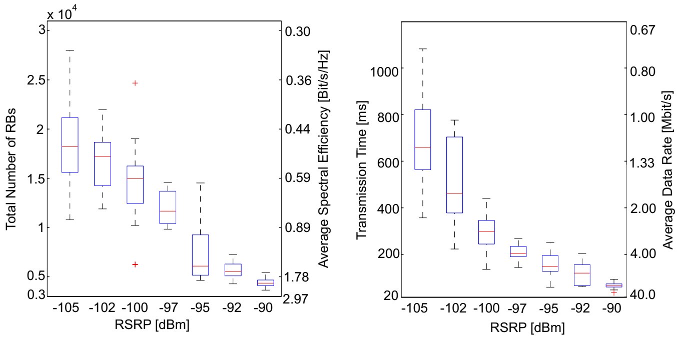

Fig. 6: Total Number of Allocated RBs, Spectral Efficiency, Transmission Time and Average Data Rate for Different RSRP Values (100 kByte Payload).

and the average RB utilization for H2H and MTC traffic (cf. Fig. 8) is calculated. It can be seen from Fig. 7 that CAT leads to a significantly lower blocking probability. Furthermore, the LTE cell utilization is much smaller for CAT (cf. Fig. 8). For example, the number of available RBs increased from 19 to 28 for an arrival rate for 10/s. This is an enhancement of 47%. The average RB utilization and blocking probability is smaller for the results from the laboratory measurements because Additive White Gaussian Noise (AWGN) channel conditions are assumed (cf. Fig. 1 for data rates). The channel conditions in the field measurements are given by the measurement positions (cf. Table II). Here, many locations are characterized by Non-Line-Of-Sight (NLOS) conditions.

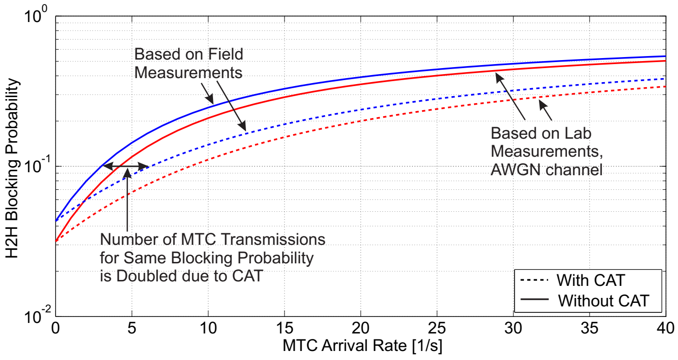

Fig. 7: H2H Blocking Probability for Channel-Aware MTC (CAT). Comparison Between Lab and Field Measurements.

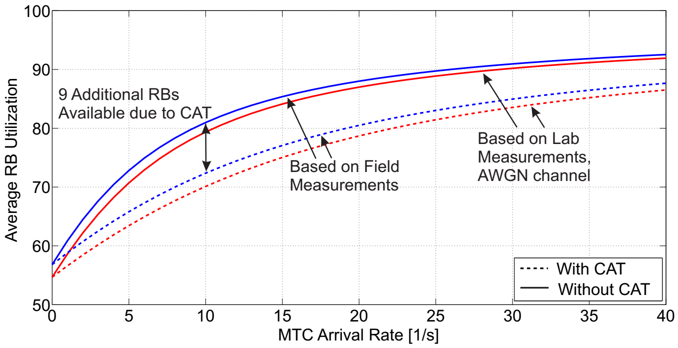

Fig. 8: Average RB Utilization for Channel-Aware MTC (CAT). Comparison between Lab and Field Measurements.

V. CONCLUSION

In this paper, we have shown a novel measurement methodology for network centric performance measurements of LTE systems. By means of the presented setup, the resource requirements of the LTE uplink for different channel conditions have been quantified. The central conclusions of this paper are:

- By applying the CAT scheme, the impact of MTC on H2H services is significantly reduced and
- CAT leads to a lower average RB utilization. This is valid for both, laboratory (cf. [3]) and field-based LTE resource requirement measurements.
- The downlink channel quality in terms of the RSRP is a suitable indicator for the required uplink resources.
- The total number of required RBs varies by a factor of four and the transmission time by a factor of eleven for an RSRP variation of 15 dB.
- For the observed LTE network, the average number of allocated RBs is a function of the channel quality and the payload size. For a small payload and a low RSRP, the number of assigned RBs is very low in contrast to better channel conditions and larger payload sizes.

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