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Measuring the Impact of the Mobile Radio Channel on the Energy Efficiency of LTE User Equipment

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***Abstract*—The energy that has to be spent for the successful submission of one Bit is an important figure of merit for the performance analysis and optimization of modern wireless communication systems. The many factors which are influencing this performance parameter range from the efficiency of the User Equipment's (UE) power amplifier to the average path loss, the Transmit Power Control (TPC) parametrization and the fading characteristics of the radio channel. Although many of the relationships can be analytically modeled, the aim of this paper is to present reliable measurements based on commercially available Long Term Evolution (LTE) hardware. Therefore, extensive User Datagram Protocol (UDP) data rate measurements have been performed in a mobile communications laboratory for different radio channel conditions. The impact of the mobile fading channel was emulated by a sophisticated radio channel emulator. Beside this, the on average consumed power of the LTE UE was measured during data transmission.**

From the results of these measurements, quantitative figures on the energy efficiency are presented for different LTE frequency bands and different radio channels. The results show that major energy savings are possible if the $800\ MHz$ frequency band, which becomes available as part of the digital dividend, can be used for user with bad channel conditions. Considering energy efficiency as a Quality of Service (QoS) parameter of increasing importance the results presented in this paper allow for a context sensitive optimization in a way that the Modulation and Coding Scheme (MCS) switching points as well as the frequency band are chosen with respect to the UE's condition.

I. INTRODUCTION

The energy efficiency of modern communication devices in terms of talk time or transferable data volume with one filling of the accumulator is one of the most important performance parameters for the customers of new devices [1]. This is the reason why extensive research has been performed in the last few years in the field of energy efficient protocols and algorithms. Prominent examples are sleep and idle modes as Discontinuous Reception (DRX) in Long Term Evolution (LTE) [2]. For the performance evaluation of these energy aware algorithms it is of major importance to have a meaningful figure of merit describing the efficiency of a communication system. One important figure in this context is the energy that has to be spent for the successful submission of one Bit. For the determination of this important performance parameter one needs to have knowledge on two different context sensitive system parameters which are the average power consumption of the User Equipment (UE) and the achievable throughput. The average power consumption of an LTE UE is a function of the transmission power per Physical Resource Block (PRB) and the number of allocated PRB per UE. While the number of allocated PRB is based on scheduling decisions the transmission power P_{Tx} is calculated by the Transmit Power Control (TPC) algorithm defined in [3]. Here, the actually emitted power is calculated as

$$P_{Tx} = min(P_{max}, P_0 + 10\log_{10}(M) + \alpha \cdot PL + \Delta_{TF} + f) \quad (1)$$

where P_{max} is the maximum transmission power allowed for LTE ($23\ dBm$ for class 3 UE [4]). The value of P_0 can be seen as the reference power per PRB for the case of no Path Loss (PL) and no additional offsets. The parameter M denotes the number of allocated PRB. The parameter PL in Equation (1) refers to the estimated path loss while the Fractional Path Loss Compensation (FPLC) factor α allows for a trade off between cell capacity and inter-cell interference [5]. The parameter Δ_{TF} represents a Modulation and Coding Scheme (MCS) dependent offset and f stands for additional Closed Loop (CL) power control commands from the eNodeB. The relationship between the transmission power and the on average consumed power for an Universal Serial Bus (USB) enabled LTE UE operating at $2600\ MHz$ is shown in [6].

The second parameter needed for the determination of the energy efficiency is the achievable throughput which is, under optimal circumstances, a function of the MCS and the number of allocated PRB. The optimum choice of the MCS on the other hand is based on the achievable Signal to Noise Ratio (SNR) at the eNodeB and therefore the path loss PL as well as the actually emitted uplink transmission power P_{Tx} and the noise level N. From this, the SNR in dB is given as

$$SNR[dB] = P_{Tx}[dBm] - PL[dB] - N[dBm] \quad (2)$$

In this paper, we present the results of extensive laboratory measurements on the achievable throughput over the LTE uplink. Therefore, a sophisticated radio channel emulator was used to investigate the impact of non-ideal channel conditions which are due to multipath fading under None Line of Sight (NLOS) conditions. The measured data rates were correlated with the on average consumed power of an LTE UE that operates at the maximum transmission power. From that, concrete figures of the energy that has to be spent for the successful submission of one Bit are derived for different LTE frequency bands and different fading channel conditions. The radio channel dependent throughput is furthermore of major importance for QoS provisioning in wireless systems.

II. Related Work

The increasing importance of energy efficiency for modern 4G communication systems leads to major challenges because battery technology is not developing as fast as the energy demand of novel high performance smart phones. Although the energy consumption of large bright displays, fast Central Processing Units (CPU) and additional sensors in modern smart-phones is continuously increasing, the major portion of the energy is consumed by the communication components such as cellular, WiFi or GPS [7]. This is the reason why extensive research has been performed in the last few years in the field of energy efficient protocols and algorithms for wireless communication systems. One prominent example is the introduction of sleep and idle modes where the device deactivates its Radio Frequency (RF) components for a predefined period of time to save energy. The LTE version of this protocol is Discontinuous Reception (DRX) as standardized in [8].

Another interesting approach for saving energy in LTE systems is described in [9]. Here, the relationship between the number of allocated PRB and the total energy that is needed for the transfer of a fixed size file is investigated for different scenarios. The results show that as many PRB as possible should be assigned to a single user to achieve maximum energy efficiency. For the derivation of the results the authors of [9] made use of the energy consumption model of a Wideband Code Division Multiple Access (WCDMA) UE presented in [10]. The assumption that this model is a valid approximation of LTE UE was needed due to the fact that there is until now no comparable energy model for LTE devices available in literature. Beside this, [9] does not consider the impact of the mobile radio channel on the achievable throughput.

Extensive investigations on the energy consumption in terms of energy per Bit have been performed in [11]. Here, the energy efficiency of an IEEE 802.16e conform Mobile WiMAX System was investigated for different transmission power, different application data rates and different file sizes. The variable parameter, which has an impact on the available data rate, is not the MCS but the downlink to uplink ratio of the Time Division Duplex (TDD) based Mobile WiMAX System.

III. Measurement Setup and Campaign

For the determination of the achievable UDP (User Datagram Protocol) data rates under different fading radio channel conditions extensive measurements have been performed in a wireless communication laboratory. A photograph of the setup can be seen in Fig. 1. The LTE Base Station Emulator (BSE) emulates the LTE air interface and

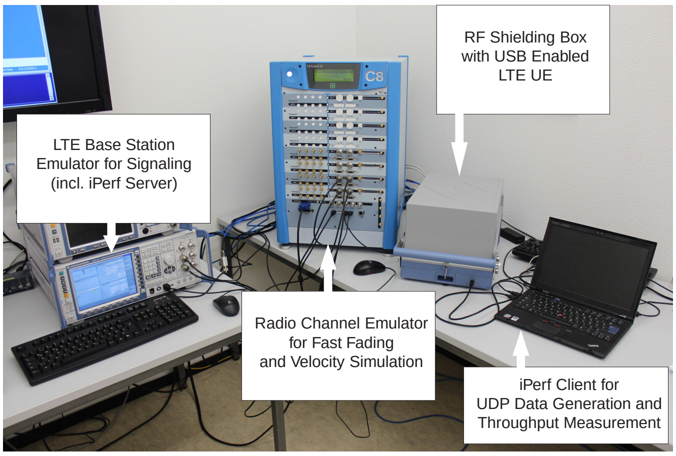

Fig. 1. Measurement Setup used for Data-Rate Measurements

allows for the establishment of an LTE standard conform radio link. All relevant parameter regarding the connection can be set here. Beside this, the BSE includes a Data Application Unit (DAU) which allows for end to end applications testing without additional hardware which might cause side effects. On the DAU an iPerf server is running which allows for reliable throughput measurements. The most important parameters which have to be set at the BSE for the data rate measurements are the TBS ID (which refers to the MCS ID as described in [3]) and the number of allocated PRB in the uplink. For the additional measurement of the on average consumed power at $P_{Tx,Max}$ the Physical Uplink Shared Channel (PUSCH) open loop nominal power was set to $23\ dBm$. For ensuring a time invariant transmission power the value of α in Eq. (1) was set to 0. The additional measurement equipment used for the power measurements as well as the methodology is described in [6].

The LTE UE that was used for the data rate measurements is a Samsung GT-B 3740 USB Stick operating in LTE Band 7 ($800\ MHz$). The on average consumed power for

TABLE I
LTE System Parameterization

BSE Parameter	Value
Carrier Frequency (UL)	847 MHz
Channel Bandwidth	10 MHz
FFT Size	1024
Duplexing Scheme	FDD
RLC ARQ mode	Unacknowledged Mode
UL MCS	Variable
UL Tx-Power	23 dBm
Allocated PRB	50
Antenna Scheme	1x1 (SISO)
Channel Emulator Parameter	**Value**
SNR	5 to 30 dB
Fading Channel Model	Extended Pedestrian A [12]
Doppler Spread	5 Hz

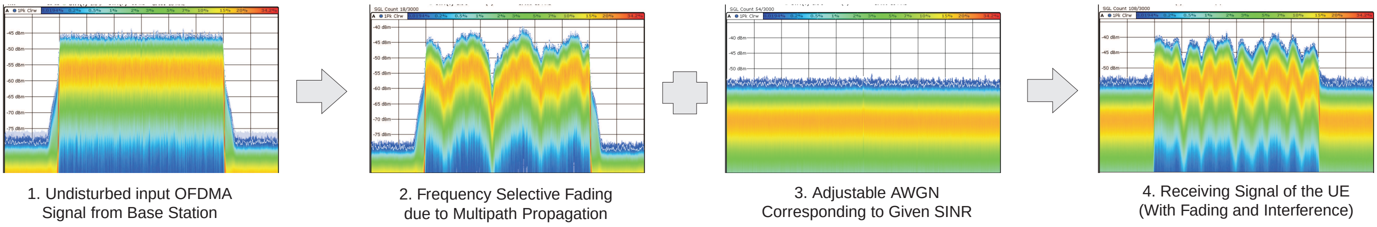

Fig. 2. Manipulation of an OFDMA Input Signal by the Radio Channel Emulator (captured by real time spectrum analyzer)

the maximum allowed transmission power $P_{Tx,Max}$ was additionally measured for the Samsung GT-B 3730 operating in LTE Band 20 ($2600\ MHz$). As it is mandatory for the throughput measurement that the impact of the mobile radio channel is fully controllable, the UE is operated inside a shielding box (see Fig. 1). This on the one hand allows for coupling the signal to an RF cable that feeds the signal to the channel emulator and on the other hand avoids any interferences from outside the measurement setup. The UE inside the shielding box is controlled by a PC which serves as UDP traffic generator (iPerf client).

Between the BSE and the UE a radio channel emulator is interconnected. This device allows for the emulation of a close to reality mobile radio channel in a laboratory environment. This includes effects such as noise and interference, Doppler-shifts due to mobility as well as fast fading due to multipath propagation. Fig. 2 illustrates the mode of operation of the emulator by means of screen shots made by a real-time spectrum analyzer. In Fig. 2.1 one can see the shape of the undisturbed OFDM signal which can be observed at the input of the radio channel emulator. Inside the device the signal is transfered to the digital baseband where it is faded referring to predefined channel models. For the investigations presented in this paper we used the Extended Pedestrian A (EPA) model defined in [12] which is specifically made for LTE performance analysis. The impact of the fast fading on the shape of the OFDM spectrum can be seen in Fig. 2.2. For the evaluation of the impact of the SNR on the LTE performance the channel emulator allows for the creation of Additive White Gaussian Noise (AWGN) corresponding to a predefined SNR. Therefore, the power of the signal after the fading is measured and the exact amount of noise that is needed for meeting the SNR requirements is created (see Fig. 2.3). At the output of the channel emulator one can observe the faded and noisy output signal shown in Fig. 2.4.

For the measurement campaign presented in this paper the SNR dependent UDP throughput was measured for 10 different MCS from TBS-ID 0 to TBS-ID 19 [3] and two different radio channel realizations: For the first measurement a pure Additive White Gaussian Noise (AWGN) channel for which the multipath fading was disabled was considered. The second measurement campaign investigates the impact of pedestrian mobility and fast fading due to NLOS conditions and multipath propagations on the achievable throughput. Therefore, the EPA channel defined in [12] was applied to the signal. The mobility was modeled by a fixed Doppler spread of $5\ Hz$. The most important parameter for the BSE and channel emulator are given in Tab. I.

IV. Measurement Results

The results of the throughput measurements for a pure AWGN channel are shown in Fig. 3. The plot shows the MCS dependent data rate for SNR from $5\ dB$ to $30\ dB$ together with the optimum MCS switching points and the corresponding envelope which describes the optimum achievable data rate assuming an optimal choice of the switching points between two MCS. One can see from the plot that the maximum achievable data rate over the LTE uplink is $21\ MBit/s$ for the parameters given in Tab. I. This value can be achieved for SNR above $25\ dB$. If the SNR is further decreased, the UE needs to switch back to a more robust MCS supporting a lower throughput. The corresponding result plot for an EPA channel is given in Fig. 4. One can see that even for very high SNR the maximum measured data rate has decreased to only $12.2\ MBit/s$. Beside this, one can observe that for the fading channel in Fig. 4 there is no constant throughput for an SNR above a specific threshold but a continuously decreasing performance for decreasing SNR. Another important observation is that the optimum switching points between the different MCS are strongly diverging from those of the AWGN channel. The optimum choice of the MCS should therefore not be performed solely based on the SNR. Having a closer look on the envelope describing the maximum achievable data rate for all SNR one can see, that MCS 10 (TBS-ID 10) does not play any role for achieving the optimum throughput. As this

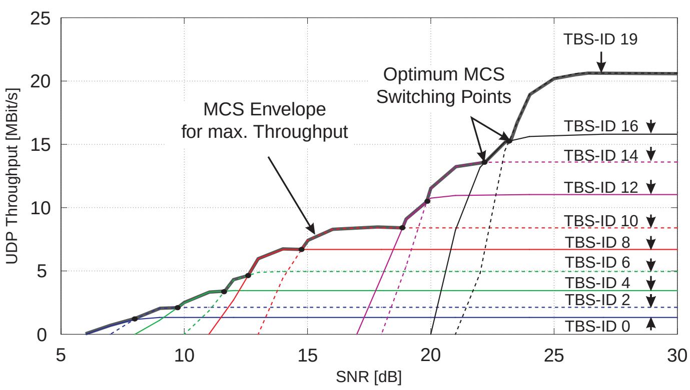

Fig. 3. MCS and SNR Dependent Throughput for Pure AWGN Channel (Derived by Measurements)

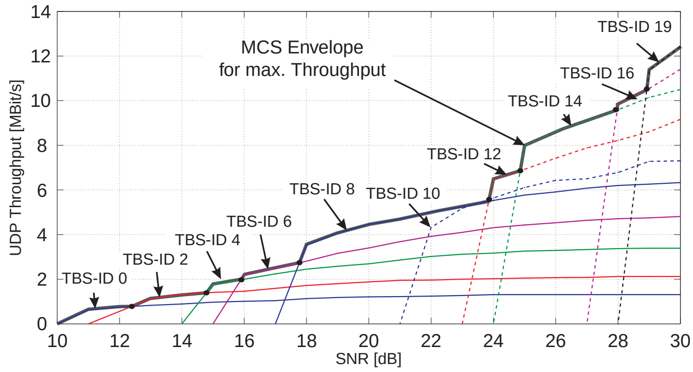

Fig. 4. MCS and SNR Dependent Throughput for Extended Pedestrian A Fading Channel (Derived by Measurements)

is the MCS with the weakest Forward Error Correction (FEC) one can state that a higher order MCS with a strong FEC performs better than a lower order MCS with a weak code. The same observation has been made for a Mobile WiMAX system in [13]. A comparison of the envelopes for the different mobile channel conditions can be seen in Fig. 5. Here, the optimum achievable data rate at the Medium Access Control (MAC) Layer is plotted together with the measured figures for the AWGN and the EPA case. For the determination of the peak MAC throughput the Transport Block Size (TBS) was determined based on the MCS and the number of allocated PRB as described in Tab. 7.1.7.2.1-1 in [3]. As one transport block can be submitted in each Transmit Time Interval (TTI) of $1\ ms$ the peak data rate in *Bit/s* is given by $T = TBS \cdot 1000$. For this case, the switching points between the MCS are taken from the AWGN measurement.

As one can see from Fig. 5 the measured throughput over an AWGN channel for the different SNR and MCS is quite close to the optimum MAC layer throughput. Nevertheless, the impact of the multipath fading is significant and leads to a throughput degradation of up to $66\ \%$ (for an SNR of $25\ dB$). Furthermore the minimum SNR for which a connection is possible increases from $7\ dB$ (AWGN) to $11\ dB$ (EPA).

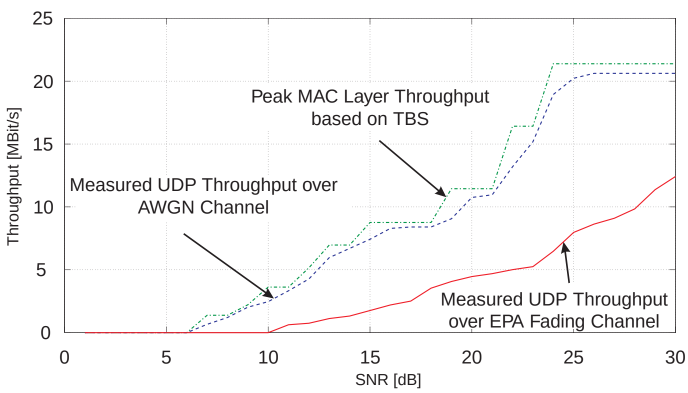

Fig. 5. Optimum Achievable Throughout for Different Mobile Radio Channels and 50 allocated PRB

V. Implications for the Energy Efficiency

In this section, the impact of the data rate for different radio channel conditions on the energy efficiency is investigated in detail. For the illustration of some important relationships Fig. 6 shows the path loss as well as the SNR at the eNodeB for different distances between the UE and eNodeB. The aim of TPC is to keep the receiver SNR at a predefined level as long as possible. Therefore, the transmission power is increased up to a maximum value that is $23\ dBm$ for LTE UE. As soon as this value is reached the SNR target can no longer be met and the SNR decreases. As one can see from Fig. 6, the distance for which the path loss can no longer be fully compensated does strongly depend on the carrier frequency. While for an UE operating at $2600\ MHz$ the SNR is decreasing for distances above $600\ m$ the target SNR of $30\ dB$ can be met up to a distance of $1.9\ km$ if an $800\ MHz$ UE is used.

Fig. 7 and Fig. 8 show the energy efficiency of the two LTE UE operating in different frequency bands for those distances between UE and eNodeB for which the target SNR can no longer be achieved (e.g. which have to be operated at $P_{Tx,Max}$). For the results the energy consumption per Bit E was calculated as

$$E(SNR) = \frac{P_{\emptyset,Max}}{T(SNR)} \qquad (3)$$

where $P_{\emptyset,Max}$ represents the on average consumed power of the LTE UE if it is operated at the maximum transmission power of $23\ dBm$. The values of $P_{\emptyset,Max}$, that were measured as described in [6] are $3.3\ W$ for the Samsung GT-B 3740 operating at $800\ MHz$ and $2.7\ W$ for the Samsung GT-B 3730 operating at $2600\ MHz$. For the throughput T in Eq. (3) the data rate referring to the optimum envelopes shown in Fig. 5 were used. The results show that the energy consumption per Bit is continuously increasing for increasing communication distances. One can see from Fig. 7 that the energy that has to be spent for the submission of one Bit in a distance of $3\ km$ is $0.4\ \mu J/Bit$ for an AWGN channel but more than $1.8\ \mu J/Bit$ for the EPA channel. This raise of $350\ \%$ comes

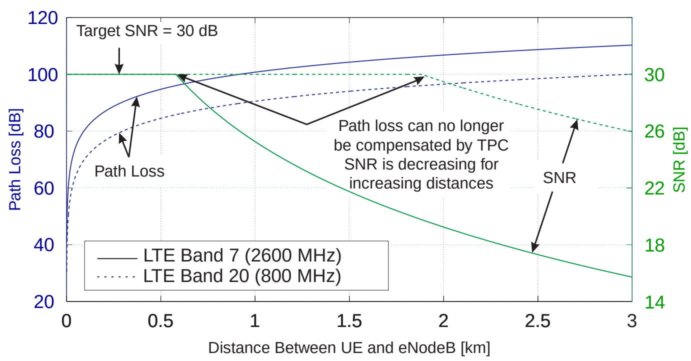

Fig. 6. Path Loss (Assuming Free Space Propagation) and SNR as a Function of the Communication Distance ($N = -120\ dBm/PRB$)

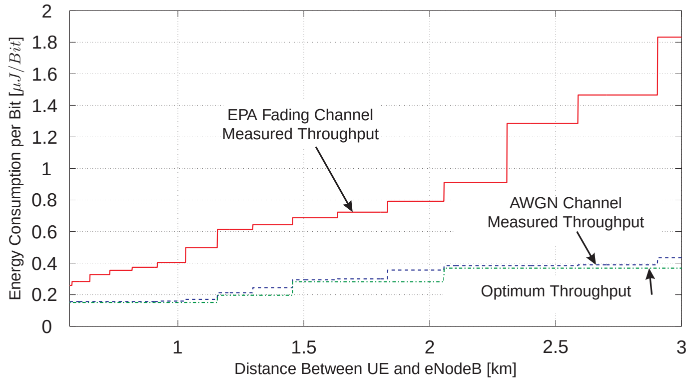

Fig. 7. Energy Efficiency of the Data Link for Variable Distances (@2600 MHz Carrier Frequency)

along with a significant degradation of the battery lifetime. One possible solution for enhancing the energy efficiency would be to handover the user with bad channel conditions to a lower frequency band (inter-Ffrequency handover). If the example UE at a distance of 3 km from the eNodeB can switch to LTE band 20 the energy consumption per Bit can be decreased to only 0.4 $\mu J/Bit$ which is exactly the value for an AWGN channel at 2600 MHz. Therefore, the major challange for network operators in the following years will be the intelligent network planing especially for the lower frequency bands.

VI. Conclusions

In this paper, we have presented the results of extensive UDP data rate measurements for the LTE uplink. Therefore, a sophisticated laboratory setup was used which allows for the introduction of close to reality mobile radio channel effects such as multipath propagation on the signal. The results have shown that the achievable throughput as well as the optimum switching points between the different MCS are strongly depending on the radio channel conditions. The so derived figures for the data rate have been applied to an energy model which allows for the calculation of the energy consumption per Bit based on the on average consumed power of a UE that is operated at the maximum allowed transmission power. The results show that the energy that has to be spent for the submission of one Bit at a carrier frequency of 2600 MHz is increasing by up to 450 $\%$ for distances between 1 km and 3 km from the eNodeB (for EPA channel). Nevertheless, we have shown that the complete performance loss can be compensated if the UE is allowed to perform an inter-frequency handover to a lower frequency band. Beside this, in this paper we have presented a generic procedure for the determination of the energy efficiency based on power consumption measurements as well as throughput measurements for real, commercially available LTE hardware.

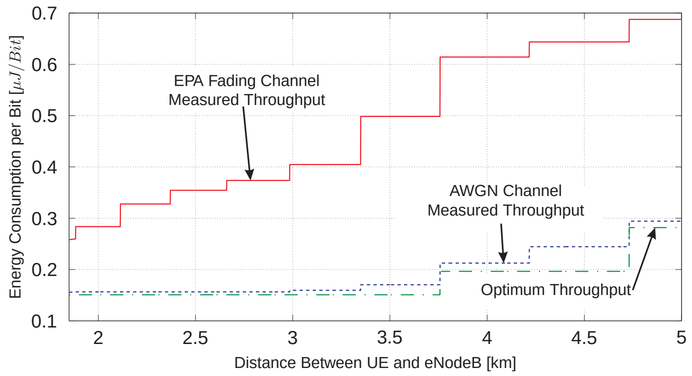

Fig. 8. Energy Efficiency of the Data Link for Variable Distances (@800 MHz Carrier Frequency)

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