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Empirical Analysis of the Impact of LTE Downlink Channel Indicators on the Uplink Connectivity

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***Abstract*—Many vehicular applications can be enabled of cellular communication networks like Long-Term Evolution (LTE). To guarantee a resource-efficient communication, the evaluation of the channel quality in the device is an important research topic in order to consider the channel quality for data transmission decisions. In this paper, the correlation between downlink channel quality indicators that are evaluated in the device and the uplink system performance is analyzed. For this purpose, theoretical analyses and field measurements in a dedicated LTE network as well as in a public LTE development are provided. The results show that the Reference Signal Received Power (RSRP) is suitable indicator for very good uplink connectivity situations and that the connectivity at the cell edge can be identified by the Reference Signal Received Quality (RSRQ).**

I. Introduction

The evaluation of the correlation between connectivity indicators of cellular communication systems (e.g., Long Term Evolution (LTE)) and the actual performance of the system is an important research topic. These analyses are from special interest for vehicular applications, because in these scenarios, the channel quality varies significantly due to the user mobility. This knowledge can be leveraged for example to improve the resource efficiency of LTE Machine-Type Communication (MTC) data transmissions in vehicular environments [1] [2] that consider the approximation of the mobile connectivity in the User Equipment (UE).

The mobile connectivity of wireless communication systems in terms of data rate or transmission time for a data packet is dependent on four main influences: The position of the UE, the environment, the interference level and the amount of data traffic by other users in the same cell. Fig. 1 shows an abstract system model that describes the performance of wireless communication systems dependent on the signal quality (position- and interference-dependent) and the network load. Dependent on the signal quality, a Modulation and Coding Scheme (MCS) is chosen by the network. This MCS leads to a spectral efficiency (SE) that describes the performance in terms of bits per second per hertz bandwidth that can be transmitted by an user in a dedicated time and frequency resource. In other words, this is the performance of a single device during an active transmission and describes the coverage of the network.

However, a cellular communication system is a Multiple Access (MA) system and besides the coverage, also the capacity limits the network performance. This means that different users have to share the available spectral resources. In LTE, Orthogonal Frequency-Division Multiple Access (OFDMA) is applied as multiple access technology. The allocation of the available radio resources is done by the eNodeB's internal scheduler. Hence, the connectivity of a single user is influenced by the number of (active) users in the same cell. Both, spectral efficiency as a result of the coverage and the assigned resources lead to the actual connectivity of the user.

For the evaluation of the channel quality in an LTE UE, several channel indicators are defined by 3rd Generation Partnership Project (3GPP). This includes the following indicators, which are generally accessible at UE's application layer:

- Reference Signal Received Power (RSRP) [dBm]: The RSRP describes the average power of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [3]. These signals are sent by the eNodeB with a constant power and they are independent of the user activity. Hence, only the position of the device influences this indicator (cf. Fig. 1).
- Receive Signal Strength Indicator (RSSI) [dBm]: The RSSI value characterizes the total reception power in the used LTE spectrum. This includes the desired signal S of all users in a cell, thermal noise N and interferences I:

$$\mathrm{RSSI} = S + N + I. \tag{1}$$

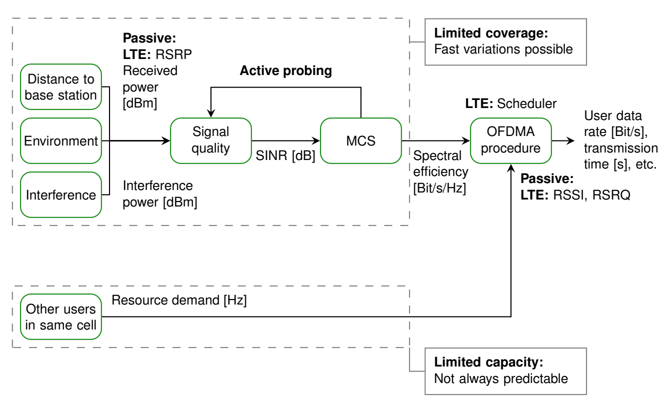

Fig. 1. Performance of Wireless Communication Systems Dependent on Signal Quality and Network Load.

- Reference Signal Received Quality (RSRQ) [dB]: The RSRQ describes the relationship between RSRP, RSSI and the number of PRBs for measuring the RSSI N_{PRB}:

$$\text{RSRQ} = 10 \log_{10} (N_{\text{PRB}}) + \text{RSRP} - \text{RSSI}. \quad (2)$$

  The RSSI and RSRQ are influenced by all three main factor for the connectivity: The position of the device, the interference situation and the data traffic produced by users in the same cell (cf. Fig. 1).

Besides theoretical analysis (cf. Section III) between passive LTE connectivity indicators and the LTE Signal-to-Interference-and-Noise-Ratio (SINR), in this paper it is shown that the downlink channel quality indicators strongly correlate with the uplink connectivity in terms of data rate. For this purpose, measurements in a dedicated LTE network are performed for different communication situations (cf. Chapter IV for measurement setup). Thereby, the distance between UE and base station, the load in the serving cell as well as the interference level of a neighboring cell are varied. The results of the measurements are presented in Chapter V.

II. Related Work

Many vehicular applications are based on cellular communication systems [4]. Besides safety applications, many of these applications are not time-critical [5]. Hence, the evaluation of the channel quality in a device inside the vehicle is important in order to increase the data transmission efficiency by leveraging the channel quality information. In addition, in context of connected cars, a local channel quality evaluation can be used to decide whether to use the local available wifi or the cellular network to transmit vehicular data. Many vehicular M2M applications are uplink dominated [6], however, the UE can only evaluate the downlink channel quality, because uplink channel quality information are only collected in the base stations. However, the UE can estimate the uplink connectivity due to the reciprocity of the radio channel (e.g, [7]). In addition, the downlink channel indicators are measured in the UE and can be estimated with an error of less than $1\,\text{dB}$ [8].

The performance of cellular communication systems are often evaluated by field trials in dedicated research networks or public networks. Test networks have the benefit that full control of the network is given, including the traffic of all users in the cell. Such measurements are performed in many cases by network infrastructure manufacturers and operators [9] [10]. However, public networks are characterized by the additional influence of others, unknown users which are also occupying network resources. In contrast to analytical models and simulations, field trials make it possible to measure the real user experience. Further LTE performance measurements are presented in [11] [12] [13]. In this paper, both, measurements in a dedicated LTE network and analyses in a public LTE deployment are performed.

III. Theoretical SINR Estimation Based on Channel Quality Indicators

In this section, the relationship between downlink channel indicators (RSRP and RSRQ) and downlink SINR is described.

SINR and RSRP Correlation

The SINR is strongly correlated to the connectivity (in terms of spectral efficiency) of a communication link and can be calculated based on the RSRP, the thermal noise N and the interference per subcarrier I:

$$\text{SINR} = \frac{\text{RSRP}}{N + I}. \quad (3)$$

Fig. 2 shows the theoretical relationship between RSRP and SINR for three different interference levels: Full interference (this means that the total power of the interference cell equals the power of the serving cell), half interference power in comparison to the serving cell power and no interference. Therefore, a two-cell scenario with a path-loss coefficient of 3 and an Inter-Site Distance (ISD) of $1732\,\text{m}$ [14] is assumed. For locations nearby the base station (thus a very high SINR) the interferences produced by neighboring cell's users is negligible, leading to the following approximation for the SINR:

$$\text{SINR} \approx \text{RSRP}/N, \qquad \text{for} \quad N \gg I. \quad (4)$$

For a RSRP of $-90\,\text{dBm}$, the error between no and full interference is only $3\,\text{dB}$. This gap is closed by the power control in a real LTE deployment. For cell-edge users, there is a large SINR range for the same RSRP values (e.g., $10\,\text{dB}$ SINR difference for an RSRP of $-110\,\text{dBm}$), caused by interference through other participants in neighboring cells. Hence, no reliable correlation is possible in this case. Therefore cell-edge users have to approximate their SINR by the use of RSRQ instead (cf. below). Furthermore, measurements in [15] strengthen the fact that the SINR is strongly correlated to the path loss (particularly for moderate SINR values), or rather, the RSRP.

SINR and RSRQ Correlation

In contrast to the SINR, the RSRQ depends on the load of the serving cell. Hence, the SINR can be calculated based on the RSRQ and the normalized load p of the serving cell [16]:

$$\text{SINR} = \frac{1}{\frac{1}{12 \cdot \text{RSRQ}} - p}. \quad (5)$$

Fig. 3 shows the relationship between SINR and RSRQ for different loads of the serving cell ($p = 1/6$ for an unloaded serving cell, $p = 7/12$ for a halfly loaded serving cell and $p = 1$ for a fully loaded serving cell [16]). It can be seen from the figure that the RSRQ is a good connectivity indicator for low SINR values. This is due to the fact that the SINR is dominated by the interference and not by the load of the serving cell for low SINR values. For high SINR values, the

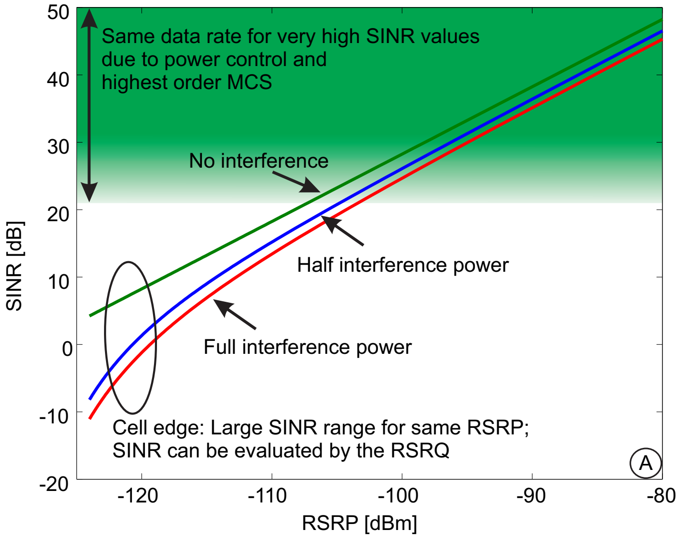

Fig. 2. Theoretical Relationship Between RSRP and SINR for Different Interference Levels in a Two Cell Scenario at 2.6 GHz, 40 dBm Transmission Power, Path-Loss Coefficient of 3 (LOS), and ISD of 1732 m.

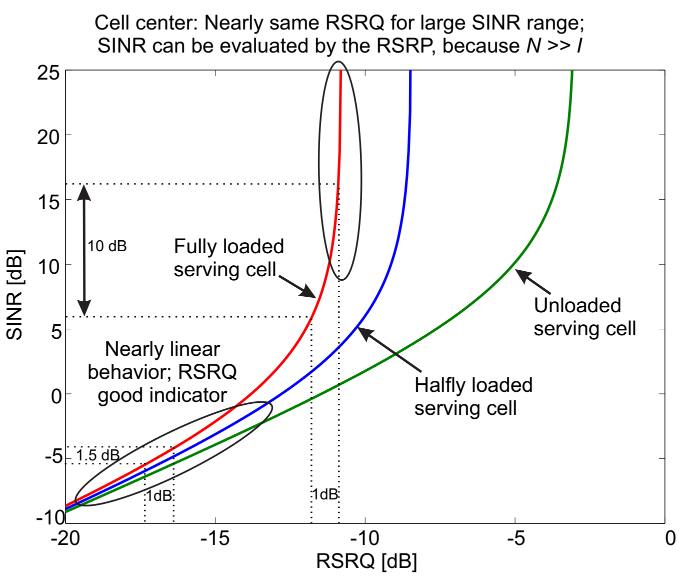

Fig. 3. Theoretical Relationship Between RSRQ and SINR for Different Serving Cell Loads.

RSRQ is not useful, because the SINR is dominated by the path loss (10 dB SINR difference results in only 1 dB RSRQ difference). The RSRQ is nearly independent of the path loss, because the influence of path loss in RSRP and RSSI is being removed due to the subtraction of these values in Eq. 2. However, the results show that the determination of the SINR for moderate channel conditions is very hard solely based on these passive indicators. Both, the RSRP and the RSRQ cannot approximate moderate SINR values with a high reliability.

IV. Measurement Setup

As described in the previous section, the downlink channel indicators can be used to approximate the downlink SINR.

TABLE I
Properties of the Dedicated LTE Network

Frequency Band	2.6 GHz (Band 7)
EIRP	158 mW (22 dBm)
Bandwidth	20 MHz (100 PRB)
Duplex Mode	FDD

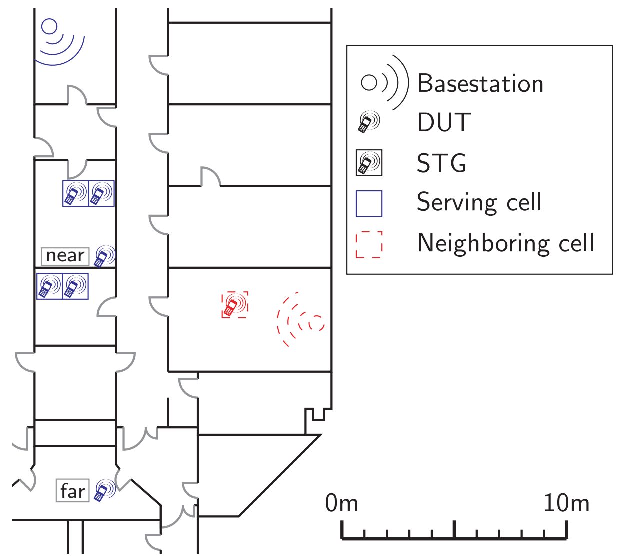

Fig. 4. Map of the Measurement Setup in an Office Building.

This section shows that the downlink channel quality indicators strongly correlate with the uplink connectivity in terms of data rate. For this purpose, measurements in a dedicated LTE network are performed for different communication situations. The configuration of the network is denoted in Table I. Due to the dedicated frequency for research purposes that is used for the measurements of this paper, there were no other activities within the selected frequency band. The measurement setup was build in our office environment which is shown in Fig. 4. It consists of two base stations running at exactly the same frequency and bandwidth, each associated with a set of UEs which are highlighted in the same way as the particular base station.

The measurements consist of the four possible extreme cases given by high and low workload of the serving and neighboring cell. Each case includes a series of measurements where the UE is being placed close to the cell center and at the cell edge. Fig. 5 shows a schematic representation of the eight different measurement setups. Within the figure, the cell's load is represented by the amount of the shown devices.

The measurements are being done by a conventional Android smartphone, referred to as Device Under Test (DUT) which is equipped with a dedicated capturing and traffic-generation application. They are repeated 50 times for each of the eight scenarios. Any single measurement consists of the connectivity indicators (RSRP and RSRQ values) during a File Transfer Protocol (FTP) data upload of 100 kB and the

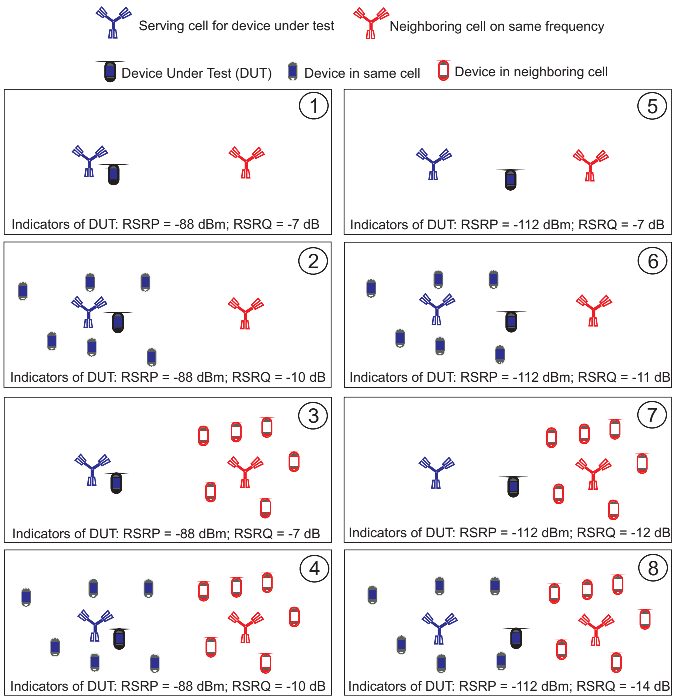

Fig. 5. Schematic Scenario Overview for LTE Connectivity Measurements in a Dedicated Real-World LTE Network.

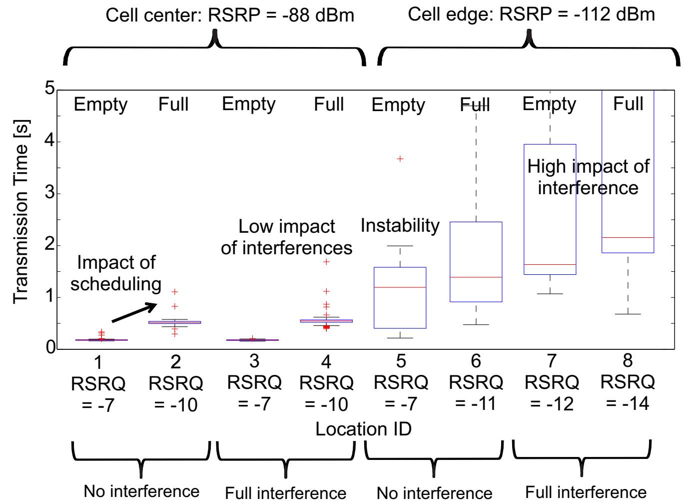

Fig. 6. Results of LTE Connectivity Measurements for Different Scenarios.

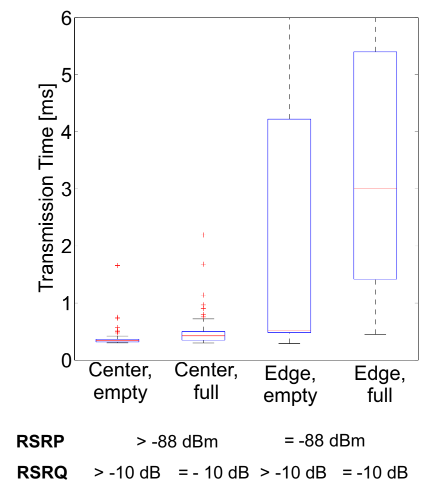

Fig. 7. Results of LTE Connectivity Measurements in a Public LTE Network for 100 kB FTP data transfer (for Main Station Scenario).

transfer time as evaluation of the actual connectivity, since it correlated directly with the incurred data rate.

The generation of background traffic is being done by Smart Traffic Generators (STGs) [17], which are locally distributed within the cells. An STG consists of a remote-accessible Embedded PC (Raspberry Pi) equipped with an LTE modem. During the experiment the appropriate STGs perform a continuous up- and downlink performance test by means of the application IPERF3 [18]. For starting the performance test each active STG opens one up- and one downlink Transmission Control Protocol (TCP) connection to a server which is located within the core network of the serving cell. After establishing the connection, both, server and client try to transfer as much data as possible to each other, controlled by the TCP's internal flow control mechanism. This results in a fully loaded cell in terms of maximum radio resource utilization.

The serving cell is loaded with four distributed STGs to create a congestive scenario for the DUT. In order to achieve a worst case interference setting a single STG, connected to the neighboring cell, was placed at it's edge towards the other cell. Since there is no resource scheduling between neighboring cells the neighbor's traffic always appears as interference, no matter of how many participants utilize all available resources.

V. Measurement Results

Fig. 6 illustrates the results of LTE connectivity measurements for the eight different scenarios. The main key contributions of these measurement results are:

- Very good uplink connectivity situations (we call them connectivity hot spots) can be identified by the downlink RSRP (compare scenarios 1-4 with scenarios 5-8).
- This is valid for all analyzed scenarios, including an empty serving cell, a full serving cell and the influence of interference (cf. scenarios 1-4).
- For a good RSRP value (cell center), the load of the serving cell scales the transmission time (compare the impact of scheduling between scenarios 1 and 2), but the influence is moderate in comparison to cell edge users (compare scenarios 5 and 7).
- At the cell edge (identifiable by the RSRP), interferences play a main role (cf. scenarios 7-8) besides the load of the serving cell. The transmission time is significantly higher compared to cell center users, under all load conditions (compare scenarios 5-8 with scenarios 1-4).
- By means of the RSRQ, the connectivity at the cell edge can be identified (cf. scenarios 5-8: The increasing median of the transmission time is correlated to an decreasing RSRQ value (from $-7\,\mathrm{dB}$ to $-14\,\mathrm{dB}$).

Measurements in a public LTE network strengthen the previous statements. Fig. 7 shows the transmission time ($100\,\mathrm{kB}$ FTP data transfer) for different networks situations with regard to the distance between base station and UE as well as the load in the network that can be identified by the RSRQ. For the measurements in the public LTE network it cannot be differentiated whether the RSRQ is influenced by users of the serving cell or inter-cell interference. However, the results underline the fact that the RSRP is a suitable indicator for a connectivity hot spot (a very stable and low transmission time can be achieved for the cell center measurements that are represented by a $\mathrm{RSRP} > -88\,\mathrm{dBm}$). For cell edge locations, the load in the network (users in the serving cell as well as interference) influence the performance of the single users significantly. Hence, the range of transmission times is much wider in comparison to the cell center measurement results.

To summarize: By means of the RSRP, connectivity hot spots (characterized by very good SINR values) can be identified. Transmissions at these hot spots enable a resource-efficient uplink communication for all investigated scenarios including different cell loads of the serving cell and different interference levels. At the cell edge, the interference level (identifiable by the RSRQ) dominates the connectivity. The SINR can be approximated based on the RSRP at the cell center and based on the RSRQ for the cell edge (here a halfly loaded cell is assumed in order to reduce the error). However, an exact mapping between a single connectivity indicator and the actual performance is not possible. The performance correlates only on average to the indicators.

VI. Conclusion

In this paper, the stochastic correlation between LTE downlink channel indicators and the uplink performance has been evaluated. Theoretical analyses show that the RSRP is a suitable indicator for the SINR for very good channel conditions. In addition, the RSRQ can be used in order to estimate the SINR at the cell edge. This behaviors has been validated by means of field measurements. Therefore, LTE connectivity measurements are performed in a dedicated LTE network in order to control the impact of the position of the device under test, the load of the serving LTE cell, and the interference situation. In addition, independent measurements in a public LTE network are provided in order to underline the identified behaviors under real-world conditions. However, passive indicators do not enable an exact forecast of the LTE performance, they only correlate to the average system performance. For an exact forecast, more indicators, e.g., based the LTE control channels, are required.

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