Deriving Cell Load from RSRQ Measurements

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***Abstract*—The performance of wireless systems is often interference-limited. In LTE, the parameter RSRQ is connected to the system interference. A solid and sound measurement of this parameter allows for an estimation of the current level of cell load as well as interference in the current cell, enabling us to use crowdsourced performance data for network benchmarking. However, RSRQ is not straightforward to interpret.**

We point out that RSRQ can be used to estimate the cell load caused by other users if it is measured at zero downlink throughput of the measuring device. In such a case we expect a positive correlation between RSRQ and achievable throughput which we confirm by measurements in a live LTE network. Conversely, we show that if the measuring device is downloading data, a wide range of different RSRQ values can be generated. As an extreme case we present measurements with strong negative correlation between RSRQ and throughput.

The source codes of the network monitoring applications are often proprietary, we thus do not know if RSRQ samples are a) collected at zero downlink throughputs, b) during a downlink throughput test or c) a combination of both. In case a) RSRQ provides us precious additional knowledge about the cell load. In cases b) and c) it is merely useless if we cannot filter out the samples corresponding to nonzero downlink throughput.

***Index Terms*—LTE, downlink, cell load, throughput, reference signal received power, received signal strength indicator, reference signal received quality, crowdsourced measurements**

I. Introduction

In the context of crowdsourced network analysis, where the measurement task is shifted towards the end user equipment (UE), we are left with a collection of several indicators and limited knowledge under which circumstances they were obtained. In LTE, the measured physical layer indicators include reference signal received power (RSRP), received signal strength indicator (RSSI) and reference signal received quality (RSRQ). Whereas RSRP is easy to interpret, the more complex RSRQ is a frequent source of misunderstanding.

In this paper, we discuss RSRQ in detail. Based on our theoretical analysis that we verified by measurements in live LTE network we give guidelines on how it can be measured and interpreted in a repeatable and meaningful way.

In Section II, based on [1], [2], we review the definition of RSRP, RSSI and RSRQ. In Section III we fix the number of OFDM[1] symbols and resource blocks (RBs) over which the RSRP and RSSI are measured, obtaining formulas similar to [3], [4]. We express RSRQ as a function of RSRP, cell load, noise + interference and we discuss concrete numerical values.

[1]Orthogonal frequency-division multiplexing.

Section IV describes our two measurement setups—a live LTE network and an unloaded reference cell. In Section V we compare the analytic results with the measurements. We find that RSRQ is impacted by our own downlink (DL) data traffic and hence it should be measured at zero DL throughput of the measuring device. This conclusion is especially important for the developers of measurement tools.

A. Related Work

Although reproduced in many existing papers, the definitions of the indicators are often misinterpreted: [5], [6] wrongly claim that the number of RBs over which RSSI is calculated depends on the number of RBs scheduled to a specific user. Others, [3], [4], consider averaging over only one OFDM symbol, although the 3GPP definitions [1] state that RSRP and RSSI can be measured over multiple symbols.

J. Salo discusses the relation between RSRQ and signal-to-interference-plus-noise ratio (SINR) in his white paper [4]. He also provides basic examples which help the reader to obtain more insight into LTE physical layer indicators. The authors of [3] simulate and verify by measurements the relation between RSRQ and SINR and between RSRP and SINR in the case of two neighboring cells and various numbers of active UEs.

RSRQ is mainly used for deciding whether an inter-frequency handover will be performed [7], [8]. In [7] the authors point out that RSRQ is heavily dependent on current system load and the measurement strategy. As explained in [4], RSRQ is not helpful for triggering intra-frequency handovers.

In [9] and [10], the authors consider RSRQ in the context of DL throughput prediction. We find that the linear model in [9] is inappropriate – RSRP and RSRQ become independent at high signal powers and proportional at low signal powers. Authors of [10] exclude RSRQ from the model, arguing with a low p-value – probably caused by measuring RSRQ improperly (at non-zero DL throughput of the measuring UE).

Several platforms measure DL throughput R and collect LTE indicators including RSRQ [11]–[13]; the authors of [10] developed their own tool. For the open source platforms—in contrast to the high-level description of proprietary tools—we can at least determine whether RSRQ was measured during a DL throughput test ($R > 0$) or during the phases with $R = 0$.

II. Terminology and Definitions

LTE eNodeBs regularly transmit a cell-specific reference signal (RS). Based on those received OFDM symbols which contain RSs, the UE estimates the physical layer indicators.

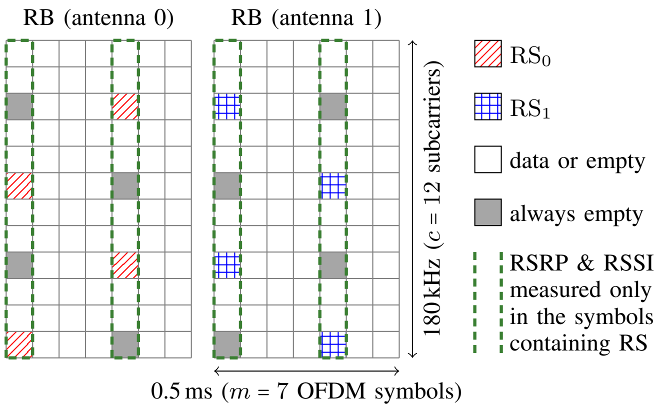

Fig. 1: One RB in the LTE resource grid in case of two antenna ports, normal cyclic prefix. The RSs are mapped to the resource grid according to [2].

A. Resource Grid

The LTE resource grid consists of resource elements (REs) of size $\Delta t \times \Delta f$ with Δt the duration of one OFDM symbol and Δf the subcarrier bandwidth (BW). There is one resource grid per antenna port.

One resource block (RB)—Fig. 1 for two antenna ports—contains $m \times c$ REs; it has the duration $m\Delta t$ and occupies the bandwidth $c\Delta f$. The RB is the smallest amount of resources which can be assigned to a user – [14, 7.1.6.].

Let cN denote the total number of subcarriers in a given channel. Then, N is the number of RBs which fit into the channel BW in the frequency dimension.

B. Cell-Specific Reference Signals

RS mappings are defined for one, two and four antenna ports, for a normal and extended cyclic prefix. RSs are transmitted in all DL subframes in a cell supporting PDSCH (physical DL shared channel) transmission. For each antenna, the REs corresponding to RSs of all other available antennas are kept empty; no signal is mapped to these REs (Fig. 1, gray shaded). See [2, 6.10.1.] for more details. In the following we denote the RSs for antenna 0 by RS_0 and the RSs for antenna 1 by RS_1.

C. Physical Layer Indicators

The RSRP and RSSI measurement BW and period are left up to the UE implementation [1]. In the f-dimension we measure over $\tilde{N}$ RBs, which we number as $n_0+1, \ldots, n_0+\tilde{N}$ with $1 \leq n_0 \leq n_0+\tilde{N}-1 \leq N$. In the t-dimension we measure over I OFDM symbols containing RS_0; numbered as $kI, \ldots, (k+1)I-1$. We do not number the other symbols.

The RSRP is defined as average power of the REs that carry RS_0,[2] measured in the antenna connector of the UE.[3] The k-th reported RSRP value can be written as

$$\mathrm{RSRP}_k = \frac{1}{2\tilde{N}I} \sum_{i=kI}^{(k+1)I-1} \left(\sum_{n=n_0}^{n_0+\tilde{N}-1} (P_{\mathrm{RS}_a,i,n} + P_{\mathrm{RS}_b,i,n}) \right), \quad (1)$$

with $P_{\mathrm{RS}_x,i,n}$ the power of the RE[4] carrying RS in the n-th RB and i-th OFDM symbol (assuming only symbols containing RS). There are always two such REs (Fig. 1), we distinguish them by $x = a$ and $x = b$. We thus average over $2\tilde{N}I$ REs.

The E-UTRA (evolved universal terrestrial radio access) carrier RSSI is the average total received power of the OFDM symbols containing RS_0:

$$\mathrm{RSSI}_k = \frac{1}{I} \sum_{i=kI}^{(k+1)I-1} (P_{S,i} + P_{Z,i}), \quad (2)$$

where $P_{S,i}$ is the total signal power (RSs and application data[5]) and $P_{Z,i}$ is the total noise and interference power, in the i-th OFDM symbol containing RS_0, both within the same measurement BW over which RSRP is measured, i.e. in the RBs $n_0, \ldots, n_0+\tilde{N}-1$.

The RSRQ is defined as

$$\mathrm{RSRQ}_k = \frac{\tilde{N} \cdot \mathrm{RSRP}_k}{\mathrm{RSSI}_k}. \quad (3)$$

We discuss its interpretation thoroughly in Section III.

III. Assumptions and Further Derivations

Assuming that the physical layer indicators are measured over the entire channel BW ($\tilde{N} = N$, $n_0 = 1$) and in every OFDM symbol containing RS (without averaging over multiple OFDM symbols, $I = 1$), Eq. (1)–(3) can be simplified:

$$\mathrm{RSRP}_k = \frac{1}{2N} \sum_{n=1}^{N} (P_{\mathrm{RS}_a,k,n} + P_{\mathrm{RS}_b,k,n}), \quad (4)$$

$$\mathrm{RSSI}_k = P_{S,k} + P_{Z,k}, \quad (5)$$

$$\mathrm{RSRQ}_k = N \cdot \frac{\mathrm{RSRP}_k}{\mathrm{RSSI}_k}, \quad (6)$$

with $P_{\mathrm{RS}_x,k,n}$ the power of the first/second RE carrying RS_0 in the n-th RB, in the k-th symbol. Here, $P_{S,k}$ is the total signal power (RS and data) and $P_{Z,k}$ the total noise + interference power of the k-th symbol. All measured at the antenna port 0.

A. Scheduled and Non-scheduled RBs

For the sake of simplicity we assume OFDM symbols contain RSs and application data, but no system information blocks (SIB) or radio resource control (RRC) messages [15].

Some RBs are scheduled to UEs, some may remain unused. Scheduled (non-empty) RBs contain RSs, application data, noise and interference. Unscheduled (empty) RBs contain only RSs, noise and interference. By non-empty REs we mean the REs containing either a RS or a data signal (+ noise and interference). Empty REs contain only noise and interference.

[2]If the UE can reliably detect that RS_1 is available, it may use RS_1 in addition to RS_0 to determine the RSRP [1].

[3]In case of receiver diversity, the reported value shall not be lower than the corresponding RSRP of any of the individual diversity branches [1].

[4]Determined from the energy received during the useful part of the symbol, excluding cyclic prefix [1].

[5]After scrambling, modulation mapping, layer mapping, precoding and resource element mapping – see Fig. 6.3-1 in [2].

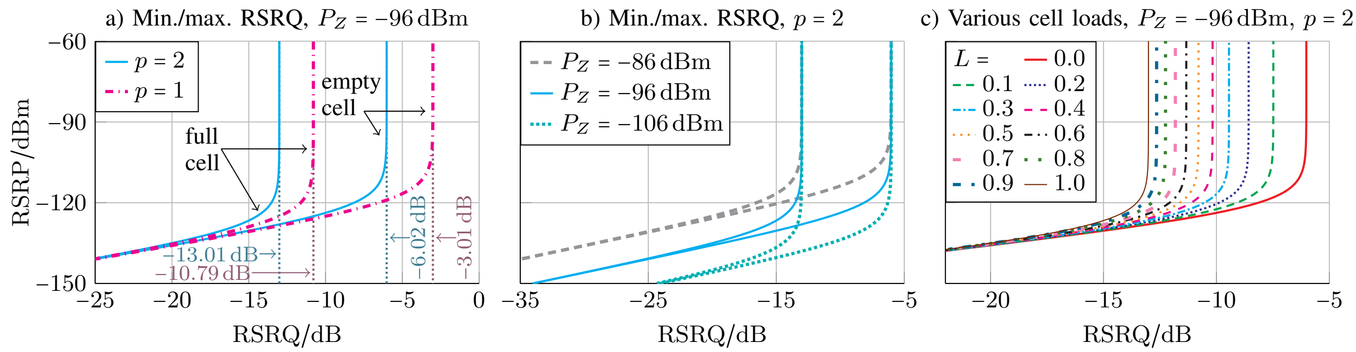

Fig. 2: RSRP vs RSRQ for different a) number of antenna ports p, b) noise and interference levels P_Z, c) cell loads L.

B. Signal Power

Let η_k denote the percentage of the non-empty REs within the k-th OFDM symbol[6] and $P_{S_l,k}$ the signal power of the l-th RE of this symbol. Assuming $\frac{1}{\eta_k c N}\sum_i^{cN} P_{S_l,k} = \text{RSRP}_k$, i.e. assuming that the average signal power of non-empty REs is equal to the average power of REs carrying RS, we can write

$$P_{S,k} = \eta_k c N \cdot \text{RSRP}_k. \tag{7}$$

$P_{S,k} = \sum_l^{cN} P_{S_l,k}$ is the total signal power in a given symbol.

Combining (5), (6) and (7), we obtain

$$\text{RSRQ}_k = \frac{N \cdot \text{RSRP}_k}{\eta_k c N \cdot \text{RSRP}_k + P_{Z,k}}, \tag{8}$$

$$\text{RSRP}_k = \frac{P_{Z,k} \cdot \text{RSRQ}_k}{N(1 - \eta_k c \cdot \text{RSRQ}_k)}. \tag{9}$$

If $\eta c N \cdot \text{RSRP}$ is much larger than P_Z, then RSRQ becomes—based on (8)—independent of RSRP:

$$\eta_k c N \cdot \text{RSRP}_k \gg P_{Z,k}: \quad \text{RSRQ}_k \to \frac{1}{\eta_k c}. \tag{10}$$

At the other extreme RSRQ becomes proportional to RSRP:

$$\eta_k c N \cdot \text{RSRP}_k \ll P_{Z,k}: \quad \text{RSRQ}_k \to \frac{N}{P_{Z,k}} \text{RSRP}_k. \tag{11}$$

C. Cell Load

Let N_k denote the number of scheduled RBs during the k-th OFDM symbol containing RSs, N is the total number of RBs in the frequency dimension. We define the cell load L:

$$L_k = \frac{N_k}{N}, \quad L_k \in [0, 1]. \tag{12}$$

The percentage η can be expressed in terms of the cell load L and vice versa:

$$\eta_k = L_k \eta_{\max} + (1 - L_k)\eta_{\min}, \tag{13}$$

$$L_k = \frac{\eta_k - \eta_{\min}}{\eta_{\max} - \eta_{\min}}, \tag{14}$$

where $\eta_{\min}, \eta_{\max}$ is the min., max. possible percentage of non-empty REs in any OFDM symbol containing RSs, respectively.

[6] $\eta_k c N$ is the total number of non-empty REs within this symbol.

D. Numerical Results

Cell specific RSs are defined for Δf = 15 kHz only [2, 6.10.1], therefore we always have $c = 12$ subcarriers per RB (for both, normal and extended cyclic prefix) [2, Tab. 6.2.3-1].

In the measurements we used the channel 2850 (20 MHz BW) [16], band 7 (frequency division duplex) [17, Tab. 5.6.1-1]. For a 20 MHz channel $N = 100$ [17, Tab. 5.6-1], we employ this value in all following simulations.

1) One Antenna ($p = 1$): If only RS_0 are transmitted, the minimum $\eta_{p=1,\min} = 1/6$: All RBs are empty, only 2 RSs per RB are transmitted in the symbols where physical layer indicators are measured (2 REs carry RS, 10 REs are empty; $2/c = 2/12 = 1/6$). The maximum is $\eta_{p=1,\max} = 1$: All RBs are full, each contains 2 REs with RS and 10 REs with data.

If noise and interference are negligible compared to signal power, we obtain from (11) the min. and max. possible RSRQ:

$$\begin{aligned} \text{RSRQ}(\eta = \eta_{p=1,\min}, P_Z \to 0) &= \frac{1}{2} \approx -3.01\,\text{dB}, \\ \text{RSRQ}(\eta = \eta_{p=1,\max}, P_Z \to 0) &= \frac{1}{12} \approx -10.79\,\text{dB}. \end{aligned} \tag{15}$$

2) Two Antennas ($p = 2$): If all RBs are empty, antenna 0 receives only RS_0 and RS_1: 4 REs contain signal, 8 REs are empty $\Rightarrow \eta_{p=2,\min} = 4/c = 1/3$. Recall Fig. 1: The REs, where the RSs for other ports are transmitted, are kept empty. The maximum the antenna 0 can receive is thus 2 REs with RS_0, 2 REs with RS_1, 8 REs with data signal for antenna 0 and 8 REs with data for antenna 1 $\Rightarrow \eta_{p=2,\max} = (2{\cdot}2{+}2{\cdot}8)/c = 5/3$.

In case of negligible noise and interference:

$$\begin{aligned} \text{RSRQ}(\eta = \eta_{p=2,\min}, P_Z \to 0) &= \frac{1}{4} \approx -6.02\,\text{dB}, \\ \text{RSRQ}(\eta = \eta_{p=2,\max}, P_Z \to 0) &= \frac{1}{20} \approx -13.01\,\text{dB}. \end{aligned} \tag{16}$$

3) RSRP, RSRQ and Cell Load: Fig. 2 a) depicts RSRP vs RSRQ based on (9) for $p = 1$ and $p = 2$ antenna ports, in the case of a full cell ($L = 1$, $\eta = \eta_{\max}$) and an empty cell ($L = 0$, $\eta = \eta_{\min}$), for a fixed P_Z. Fig. 2 b) illustrates the impact of P_Z. In the logarithmic scale, the RSRP as a function of P_Z in (9) differs only by a constant term $10\log(P_Z)$. Fig. 2 c) shows RSRP vs RSRQ for various cell loads L.

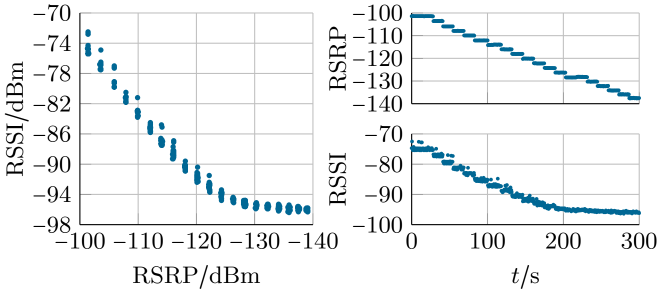

Fig. 3: Measuring noise and interference level P_Z in an unloaded reference cell. At low RS powers (low RSRP) the RSSI saturates and it corresponds to P_Z, see (17).

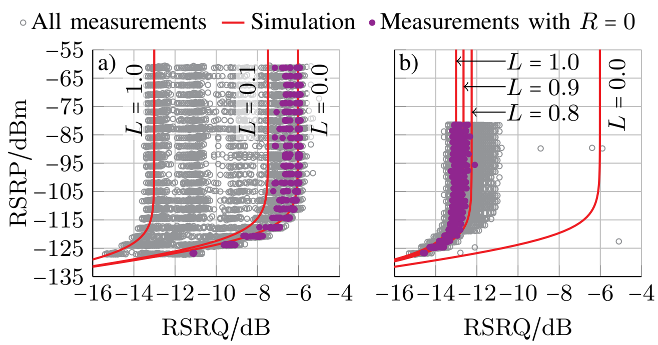

Fig. 4: RSRP vs RSRQ in the reference cell at $P_Z \approx -96\,\text{dBm}$ with a) 1 UE active, b) 7 UEs active. RSRQ is useful for determining the cell load if we consider only the samples collected at the zero throughput $R = 0$ of the measuring UE (purple filled). Considering all samples (gray empty) yields larger RSRQ ranges in b) and all possible RSRQs in a).

In (10), RSRQ becomes inversely proportional to η, independent of RSRP and it is useful for estimating L from (10), (14). In (11), RSRQ becomes independent of L and proportional to RSRP; in this region RSRP and RSRQ can be used to estimate the noise + interference P_Z from (11).

IV. Measurement Setup

We passively collected the LTE physical layer indicators and performed active DL throughput measurements. In the reference cell we collected the passive information with the NEMO smartphone and software [18]. In the outdoor campaign we used a conventional smartphone (much cheaper than NEMO) and gathered the values reported by Android at the application layer (lower resolution than NEMO).

In both setups we used iPerf3 [19] to generate the DL traffic and to measure the throughput: Each measurement consisted of five parallel TCP connections (sufficiently fast throughput ramp-up) and took 10 s. The TCP congestion control algorithm was set to CUBIC.[7] The iPerf3 daemon was running on our own server at Institute of Telecommunications, TU Wien.

[7] Default in Linux kernels [20]. Android is based on Linux kernel [21].

A. Reference Cell

In this setup we used our own eNodeB and took measurements in an anechoic chamber to have full control of which UEs are registered in the cell. The two antenna ports of the measuring UE (Samsung Galaxy Note 4 [22], LTE Cat. 4) were connected to the eNodeB (Nokia, LTE 2.6 GHz, band 7, channel 2850, BW 20 MHz) with cables through a tunable attenuator which allowed us to achieve arbitrary RSRP levels.

The eNodeB was connected to the live LTE network of an Austrian operator. While having full control of the cell, the rest of the network stayed realistic. In the first case there was just the measuring UE in the reference cell. In the second case, in order to simulate cell load caused by other users, we included six other UEs (connected wireless) which were permanently generating DL traffic at the maximum possible throughput.

B. Outdoor Measurements

As the second dataset we took the measurements collected in 2016 in a rural area (Kindberg, AT, GPS: 47.5093, 15.4569). The UE (LG K4 [23], LTE Cat. 4) was locked in a shielded box (rain protection) with two external antennas and connected wireless to an eNodeB in a normal, fully operational cell, allowing us to observe the varying cell load during the day.

V. Measurement Results

A. Reference Cell

1) Measuring P_Z: The noise and interference power can be estimated from (11) or from RSSI at low signal power P_S:

$$\text{based on (5):}\quad P_{S,k} \ll P_{Z,k} \quad\Rightarrow\quad \text{RSSI}_k \to P_{Z,k}. \qquad (17)$$

Low P_S is achieved by generating no DL data traffic and by decreasing the RS power (decreasing the RSRP) sufficiently. Increasing the attenuation, we reach the region where the RSSI saturates and is impacted only by the noise + interference.[8] In Fig. 3 we can directly read out $P_Z \approx -96\,\text{dBm}$.

2) RSRP, RSRQ and Cell Load: The scatter plot in Fig. 4 a) depicts RSRP and RSRQ measured when there was one UE active. In b) there were 6 more UEs active. It might be surprising that the samples in a) cover all possible cell loads L (gray empty circles). This is because the percentage η as defined in Section III-B and the load L as defined in (12) do not distinguish our own traffic from the traffic generated by others. If our single UE is downloading no data, the cell load is $L = 0$. If the UE is downloading at the full rate, $L = 1$. Despite transmitting at the max. possible rate, the throughput is bursty and shows fluctuations[9] resulting in a varying number of scheduled RBs, i.e. in different cell loads.

Considering only RSRQ collected when the measuring UE was not downloading any data, we get a more informative picture: $L \in [0.0, 0.1]$ (purple filled circles). With other UEs active, plot b), we see cell load $L \in [0.8, 1.0]$ when measuring RSRQ without injecting our own data.

[8] RSRP does not saturate, although the power of REs carrying RSs also contains noise + interference. The reason is that the UE can exploit the known RS structure (e.g. coherent detection) achieving higher sensitivity.

[9] We use our own cell, but the rest of the connection – through the LTE core network and the Internet up to the iPerf3 server – is a live network.

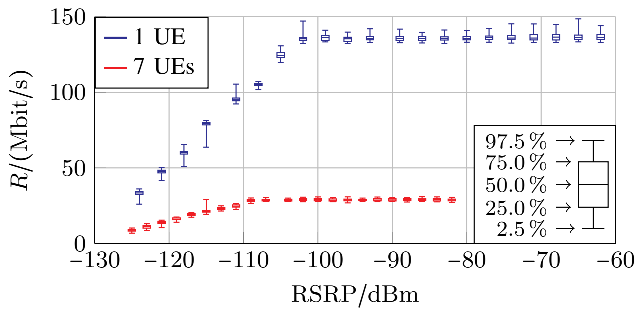

Fig. 5: Max. achievable DL throughput measured in the reference cell. Blue: only one UE active. Red: 7 UEs active.

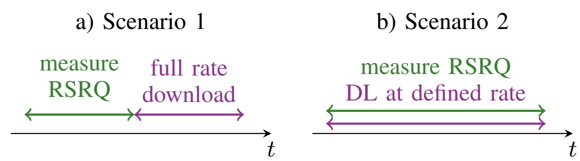

Fig. 6: a) RSRQ was measured properly (zero DL throughput). b) RSRQ was collected while data were being downloaded.

3) RSRP and Throughput: Fig. 5 (blue) depicts the throughput measured by iPerf3 with only one UE active in the cell. For each RSRP we took ≈ 100 measurements, the boxes illustrate the distributions of the measured values. The saturation near 150 Mbit/s is present because our UE is LTE Cat. 4.

If P_Z is constant, the SINR is proportional to RSRP. After considering all nonidealities (BW efficiency, LTE SNR implementation efficiency) we can calculate the capacity of an additive white Gaussian noise channel [24]. However, P_Z is in practice not constant: moving away from an eNodeB, coming closer to the cell edge, usually results in decreasing RSRP (higher path loss) and increasing P_Z (receiving more interference from a neighboring cell), see, e.g. [3, Fig. 2].

We can thus view RSRP as an indicator of a maximum achievable throughput under perfect conditions (no other users in the home cell, no interference from neighboring cells, constant noise power), even though an exact calculation of the throughput R as a function of RSRP is not trivial and depends on many, in practice unknown, circumstances.

4) RSRQ and Throughput: RSRQ is useful for determining the cell load L. In Fig. 4 we have seen that just a single UE is enough to fill all RBs ($L = 1$). If there are d active UEs, all requesting the same amount of resources and having the same channel conditions, we expect under the assumption of fair scheduling $\approx 1/d$ of the maximum available throughput, even though we always observe $L = 1$ regardless of d.

Fig. 5 (red) shows the measured throughput when there were 6 other active UEs in the cell. In the region where R grows we reach ≈ 26 % and in the saturation region ≈ 21 % of throughput compared to the case with only 1 UE.[10]

[10]This does not correspond to $1/d = 1/7$ because all UEs have slightly different channels (the measuring UE connected with cables, all others wireless), experiencing different RSRPs.

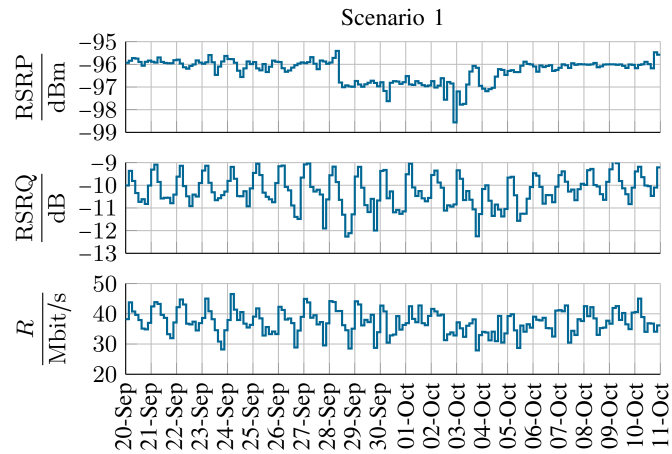

Fig. 7: Results of a long term, outdoor measurement in a live LTE network. RSRQ samples were collected when the DL throughput was zero. Bin size = 3 hours.

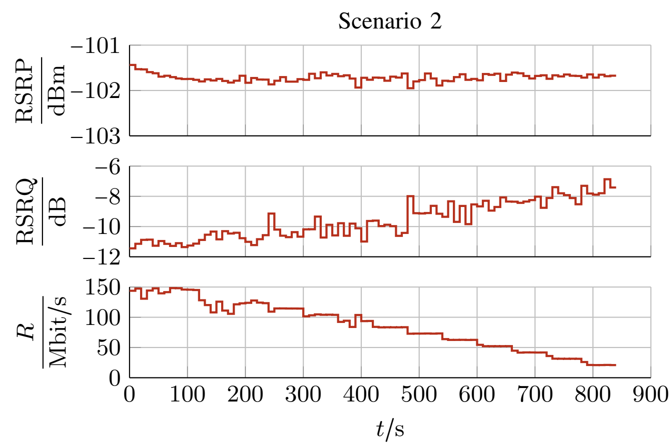

Fig. 8: Measurement in an unloaded reference cell. In regular, 60 s intervals the DL throughput generated by iPerf3 was decreased, resulting in the increasing RSRQ. Bin size = 10 s.

B. Outdoor Measurements

If we measure RSRQ at $R = 0$, Fig. 6 a), at fixed RSRP, we expect a higher R for a lower L (higher RSRQ). This is confirmed by our outdoor measurements (Fig. 7). We selected a time interval with relatively stable RSRP. The signals have been binned to 3 hour intervals to suppress short-time fluctuations (real cell, live network), the remaining trend shows positive correlation[11] ($r = 0.73$) between R and RSRQ. Clear diurnal pattern is visible.

C. Two Extreme Cases

To emphasize the importance of measuring RSRQ at $R = 0$ we performed an alternative measurement which violates this requirement, Fig. 6 b). In the reference cell with only one UE active we repeatedly executed iPerf3, setting up a lower

[11]Sample correlation coefficient $r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}$.

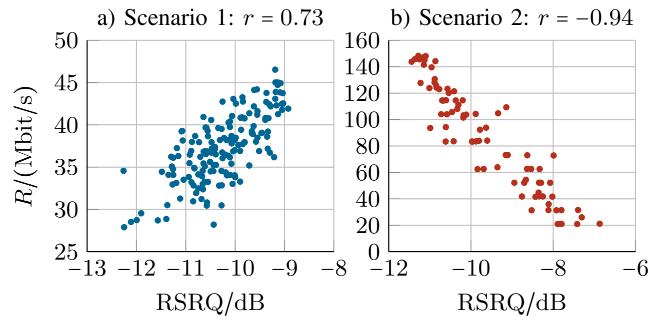

Fig. 9: In scenario 1 the R and RSRQ show a strong positive correlation, in scenario 2 a strong negative correlation.

and lower target throughput (an additional `-b` option) in every iteration. Fig. 8 shows the measurement results, bin size = 10 s. Here, RSRQ measures nothing else than our own throughput, the correlation between R and RSRQ is hence negative ($r = -0.94$). The scatter plots in Fig. 9 compare both scenarios.

VI. Conclusion

In order to bridge the gap between a network-centric and a user-centric (e.g. crowdsourced network benchmarking) view of performance of LTE networks, we need to interpret several physical layer indicators: RSSI comprises the total power in one OFDM symbol. RSRP measures the path loss. RSRQ depends on RSRP, on the current traffic load in the home cell and on the noise + interference level P_Z. By measuring RSRQ, RSRP and P_Z we can determine the current cell load. We have derived these dependencies analytically and verified them with measurements.

Furthermore, we have analyzed the dependence of the throughput on the RSRP, RSRQ and cell load. At a given noise level, RSRP can be seen as an indicator of achievable throughput under perfect conditions (no cell load, no interference from neighboring cell). At fixed P_Z and fixed RSRP level, the RSRQ and throughput are positively correlated (if RSRQ is measured properly).

We have shown that RSRQ is meaningful only if we do not generate any DL data traffic during its measurement. Otherwise the range of the reported RSRQ values is broadened and in the case of an empty cell even arbitrary RSRQ values (from the, by RSRP allowed, interval) can result from the download activity. As an extreme case we have shown a scenario where RSRQ and throughput are negatively correlated.

Although many network monitoring tools [11]–[13] measure RSRQ, it is not clearly stated at which measurement phase the RSRQ samples are collected. This paper gives a clear guideline for the developers of measurement tools: RSRQ should be measured at zero DL throughput and the high-level description of the measurement tools should contain information on how the RSRQ was measured.

Due to its complexity, RSRQ is often misinterpreted (linear model in [9] is not appropriate, there is a region where RSRP and RSRQ are proportional as well as a region where they are independent) or ignored (low p-value in [10, IV-A-2]).

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References

[1] 3GPP, “Physical layer; Measurements,” TS 36.214, version 15.1.0.
[2] ——, “Physical channels and modulation,” TS 36.211, version 15.1.0.
[3] C. Ide, R. Falkenberg, D. Kaulbars, and C. Wietfeld, “Empirical analysis of the impact of LTE downlink channel indicators on the uplink connectivity,” in *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, May 2016, pp. 1–5.
[4] J. Salo, “Mobility parameter planning for 3GPP LTE: Basic concepts and intra-layer mobility, white paper,” Jun. 2013. [Online]. Available: http://www.lteexpert.com/lte_mobility_wp1_10June2013.pdf
[5] R. Subramanian, K. Sandrasegaran, and X. Kong, “Benchmarking of real-time LTE network in dynamic environment,” in *2016 22nd Asia-Pacific Conference on Communications (APCC)*, Aug. 2016, pp. 20–25.
[6] V. Sevindik, J. Wang, O. Bayat, and J. Weitzen, “Performance evaluation of a real long term evolution (LTE) network,” in *37th Annual IEEE Conference on Local Computer Networks - Workshops*, Oct. 2012, pp. 679–685.
[7] J. Kurjenniemi, T. Henttonen, and J. Kaikkonen, “Suitability of RSRQ measurement for quality based inter-frequency handover in LTE,” in *2008 IEEE International Symposium on Wireless Communication Systems*, Oct. 2008, pp. 703–707.
[8] H. Xian, W. Muqing, M. Jiansong, and Z. Cunyi, “The impact of channel environment on the RSRP and RSRQ measurement of handover performance,” in *2011 International Conference on Electronics, Communications and Control (ICECC)*, Sep. 2011, pp. 540–543.
[9] J. Cainey, B. Gill, S. Johnston, J. Robinson, and S. Westwood, “Modelling download throughput of LTE networks,” in *39th Annual IEEE Conference on Local Computer Networks Workshops*, Sep. 2014, pp. 623–628.
[10] K. Uludağ and O. Korçak, “Energy and rate modeling of data download over LTE with respect to received signal characteristics,” in *2017 27th International Telecommunication Networks and Applications Conference (ITNAC)*, Nov. 2017, pp. 1–6.
[11] RTR – NetTest. [Online]. Available: https://www.netztest.at/en/
[12] Netradar. [Online]. Available: http://www.netradar.com/
[13] OpenSignal. [Online]. Available: https://opensignal.com/
[14] 3GPP, “Physical layer procedures,” TS 36.213, version 15.1.0.
[15] ——, “Radio resource control (RRC); Protocol specification,” TS 36.331, version 15.1.0.
[16] RTR – Spectrum – Distribution of operators. [Online]. Available: https://www.rtr.at/en/tk/FRQshare
[17] 3GPP, “User equipment (UE) radio transmission and reception,” TS 36.101, version 15.2.0.
[18] Nemo handy handheld measurement solution. [Online]. Available: https://www.keysight.com/en/pd-2767485-pn-NTH00000A/nemo-handy
[19] iPerf. [Online]. Available: https://iperf.fr/
[20] CUBIC TCP – Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/CUBIC_TCP
[21] Android (operating system) – Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Android_(operating_system)
[22] Samsung Galaxy Note 4 – Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Samsung_Galaxy_Note_4
[23] LG K4 LTE Smartphone | LG Österreich. [Online]. Available: http://www.lg.com/at/handys/lg-K120E-k4-lte
[24] P. Mogensen, W. Na, I. Z. Kovacs, F. Frederiksen, A. Pokhariyal, K. I. Pedersen, T. Kolding, K. Hugl, and M. Kuusela, “LTE capacity compared to the Shannon bound,” in *2007 IEEE 65th Vehicular Technology Conference – VTC2007-Spring*, Apr. 2007, pp. 1234–1238.