Application Level Performance Measurements of Multi-Connectivity Options in Cellular Networks for Vehicular Scenarios

Ralf Lübben
Flensburg University of Applied Sciences
Flensburg, Germany
Email: ralf.luebben@hs-flensburg.de

Jens Schwardmann
Robert Bosch GmbH
Hildesheim, Germany
Email: jens.schwardmann@de.bosch.com

***Abstract*—Intelligent Transportation Systems (ITS) and vehicle passengers request for high-speed and reliable data access from vehicle to infrastructure networks. For example, passengers like to consume multimedia services and new use cases arise from ITS and connected vehicular services that require high-speed and reliable connectivity solutions. To achieve these requirements multi-connectivity is a viable solution to increase throughput and reliability. Such options exist on various layers. On the network access layer multiple antennas are deployed for transmitting and receiving data in parallel data streams; on the transport layer different network access opportunities are utilized by multi-path protocols such as multi-path TCP. At the present study, we evaluate performance metrics of these options in a real-world vehicular scenario. We quantify throughput, delay, and reliability improvements of using multiple antennas and multi-path TCP and also indicate issues of multi-path TCP. Further, we demonstrate performance improvements by the change of the congestion control protocol.**

I. Introduction

Wide area cellular networks are ideal to deliver high-speed network access to passengers in vehicular scenarios and provide reliable connections for ITS use cases. The cellular standard Long Term Evolution (LTE) and the upcoming standard 5G build the base for high throughput mobile networks. To improve throughput, reliability, and latency multi-connectivity is one solution for such improvements. Here, we provide an analysis of multi-connectivity options in existing protocol stacks and their benefit in a real-world vehicular scenario.

In this paper, we evaluate the real-world performance of cellular networks for such scenarios. The first option we value is Multiple-Input Multiple-Output (MIMO). Amongst others, it is integrated at the network access layer in current releases of the LTE cellular standards. LTE supports Single-Input Single-Output (SISO) and MIMO antenna setups. SISO provides a single data stream between one send antenna and receive antenna pair, whereas MIMO setups provide multiple independent data streams on the same frequency between multiple antenna pairs, e.g., a 2x2 setup with two sending and two receiving antennas provides up to twice the throughput compared to an equivalent SISO setup. This theoretical upper bound is achieved if the signal paths are uncorrelated, however, in practice correlation occurs. We evaluate the improvement of a MIMO setup by application level measurements. The second multi-connectivity option that we assess, are multi-path transport protocols such as the multi-path Transport Control Protocol (MPTCP) [1] or extensions to the recently introduced transport protocol Quick UDP Internet Connections (QUIC) [2], [3]. Here, we limit the analysis to MPTCP. Still results may be transferable to QUIC, due to similar scheduling and congestion control algorithms.

For these two options, we contribute an evaluation of the performance. We evaluate the real-world benefit of a MIMO setup in a vehicular scenario that includes rural as well as urban environments. We compare both setups by throughput and round trip time (RTT) measurements. We further determine metrics like handover events, connection and packet loss frequency. For MPTCP, we compare the throughput of individual mobile network operators (MNOs) to the throughput achievable by aggregation of several MNOs.

The rest of the paper is structured as follows. Sec. II describes the measurement setup used for all measurements. In the first part of the analysis presented in Sec. III, we compare SISO and MIMO antenna setups. In the second analysis part in Sec. IV, we evaluate the throughput of an MPTCP connection that aggregates three independent cellular connections to the throughput of the individual connections. Sec. V describes the work related to field measurements for multi-connectivity options. Sec. VI concludes the paper.

II. Measurement Setup

For the measurements a vehicle is equipped with an x86 mini computer (Compulab Fitlet2). As LTE modem the Sierra Wireless EM7565 is used. It is an LTE category 12 modem and supports UMTS as fallback. For measurements of the position and accurate time synchronization the embedded global navigation satellite system receiver included in the modem is used. One modem is built into the computer. Additional two modems of the same type are connected via separated universal serial buses for application layer multi-path measurements. Each modem is connected to two antennas (Laird TRA6927M3NB) which are mounted on the vehicle roof. We measure the downstream TCP performance. For the

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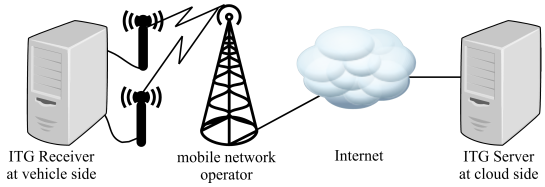

Fig. 1. Measurement setup

data rate measurements the traffic generator D-ITG [4] is used. It requires the specification of a traffic profile, which we configure with a constant rate of 120 MBit/s for three seconds. The traffic is generated at the server and the arrival rate is measured by recording the traffic at the computer in the vehicle. The rate at the receiver is measured in intervals of 250 ms but only the measurement from the last interval is extracted since here we expected TCP slow start to be finished, which is further evaluated in [5].

The rate measurements are consolidated with the position recorded simultaneously. Since the position is measured only each second, the position of the rate measurement is interpolated between the position measured before and after the rate measurement based on the timestamp included in each measurement. For comparison, the measurements are attributed to a map tile based on the position. The mapping to a tile is based on the algorithm from [6], resulting tiles have a size of about 178 m in height and width.

The server is synchronized in time by the network time protocol. The setup is illustrated in Fig. 1. For the measurements two antennas are connected to each modem, for the SISO setup the second path is disabled programmatically.

Of most interest are regions where low data rates are expected, since they are most critical for applications that require a continuously high data rate. This is mostly expected in rural areas, where cell sizes are large and coverage may be intermittent. Therefore, we selected an area for the drive tests in a mostly rural area between German cities Flensburg and Kiel. It consists mostly of highway segments and partly non-highway segments. The typical speed driven on the highway segments was about 120 km/h. The track length is about 94 km yielding a usual duration of a drive of about 55 minutes. The surroundings of the rural highway segments are flat with base stations often located close to the highway. Such conditions are prone to line of sight conditions.

III. Comparison SISO vs. MIMO

On the LTE layer, single and multiple paths are provided by using a SISO and MIMO antenna setup, respectively. In the ideal case, in which the channel between multiple antennas is uncorrelated, a 2x2 MIMO antenna setup doubles the throughput. However, if correlation occurs between the different paths, less throughput than in the ideal case is achieved.

First, we evaluate in this section the throughput gain by application layer measurements as explained in Sec. II. Second, we examine the delay performance by RTT measurements.

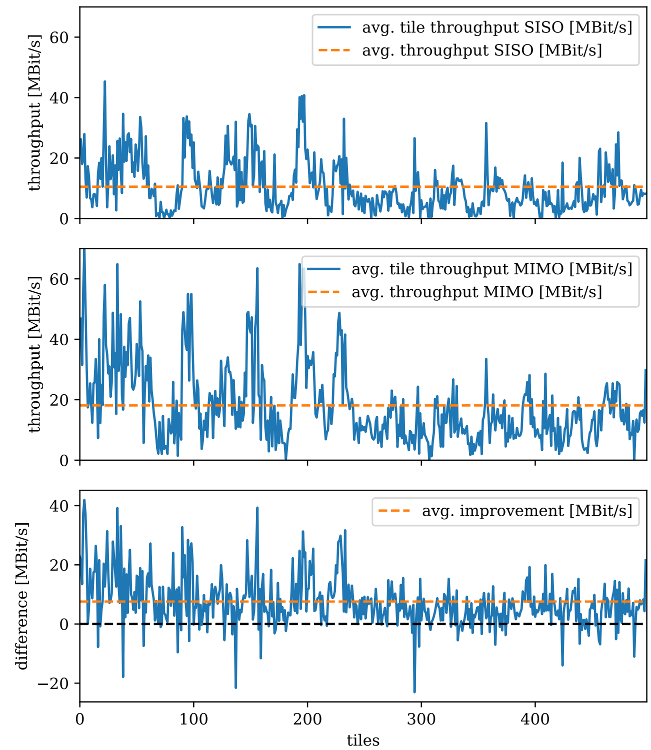

Fig. 2. Throughput in average per tile and overall of the SISO and MIMO antenna setup together with the difference per tile. In most of the cases MIMO improves the throughput. Still a correlation of the throughput in equal tiles between both setup is indicated.

Third, we analyze the reliability of the connection by observation of handovers and delays.

A. Throughput

The throughput using a MIMO antenna setup increases in average by a factor of 1.72 from 10.52 MBit/s to 18.11 MBit/s as depicted in Fig. 2. The average values result from 1450 samples for the SISO setup and 2029 for the MIMO setup. This indicates that the theoretical throughput gain of MIMO is nearly achieved in real-world scenarios.

Even in this scenario, where most of the track is a highway in a rural and flat area, the gain is large. To achieve this gain, uncorrelated channels are required, whereas correlation increases, e.g., if Line-of-Sight (LoS) conditions contribute significantly to the channel matrix [7]. This indicates that even at this track where LoS conditions are expected due to cell towers close to the highway, channels seem to be mostly uncorrelated since the throughput increases significantly.

B. Latency

Latency is another important network characteristic besides throughput. Here, we compare the impact of using a SISO or a MIMO setup on the RTT. The RTT is measured by the use of the utility *ping*, i.e., utilizing the Internet Control Message Protocol (ICMP). For each sample, the RTTs of three ICMP echo request/echo response packet pairs are averaged. The echo requests are sent with an inter-departure time of 200 ms.

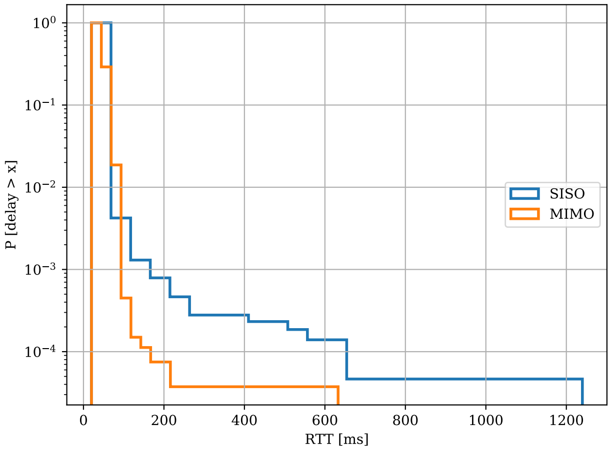

Fig. 3. Histogram of the complementary cumulative distribution function of RTT measurements for SISO and MIMO antenna setup. The MIMO setup reduces the RTT especially in range above 100 ms. Still, the probability of RTTs above 100 ms is about 1%.

Overall, 21534 samples were collected for the SISO setup from 6 rides and 26804 samples from 8 rides for the MIMO setup. The complementary cumulative distribution function (CCDF) of the RTTs in Fig. 3 shows that the probability of large delays decreases in a MIMO setup. For both setups, the probability of delays greater than 100 ms is about 1%. Variations in the range below 100 ms are often caused by the LTE protocol stack as highlighted in [8]. Moreover, the MIMO setup reduces the packet loss ratio from 4.5e-3 for the SISO setup to 1.1e-3. The reduction of packet loss indicates a better reliability of the MIMO setup, which we evaluate further in the next section.

C. Connection Loss

Coverage gaps exist that lead to a deregistration of the modem. The used modem manager Ofono and connection manager ConnMan removes the network interface configuration of the related network interface, which leads to a drop of TCP connections. On our measurement track, the coverage gaps are little and the related network interface is reconfigured fast, i.e. in less than 1 s and often with the same IP address. Such deregistration events occur about 50 times on each track for the SISO setup and about 5 times for the MIMO setup. These results again show that the MIMO setup increases the reliability of the connection. Besides the modem deregistration events, we further evaluate packet losses. To measure the latency in the previous section, we used three ping packets. In Fig. 4, we show the loss events of one packet in dark green, and two loss events in red. The number of handover events is shown as a heatmap in the background. As before, the results demonstrate a relationship of handover events and losses, where losses occur frequently in regions with handovers. For SISO 0.45% of 21534 measurements show one or more losses and for MIMO 0.097% of 26804 measurements show one or more losses.

Overall, a MIMO setup significantly increases the reliability of the connection in terms of modem deregistration events and

(a) SISO (b) MIMO

Fig. 4. Relation of handover events and packet losses. One packet loss of three packets is indicated by dark green dots, two loss events of three packets is indicated by red dots. The blue background indicates handovers as heatmap, dark blue means more handovers. Map data: ©OpenStreetMap

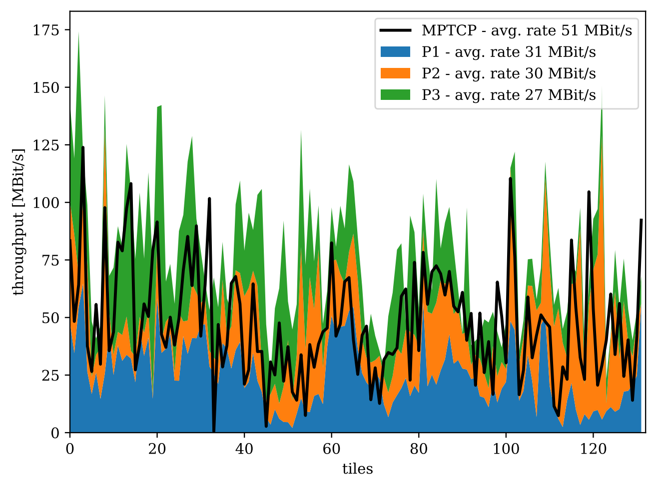

Fig. 5. MPTCP throughput compared to single MNO throughput and the sum of the three MNOs. The sum for all MNOs is in most cases higher than the MPTCP throughput. At least one sample exists in each tile for each MNO or MPTCP measurement. The average rate is given in the legend.

packet losses. First, less deregistration events occur, second, this reduces the deletion of the network interface configuration, and third, less losses occur. Nevertheless, regions with poor performance still exist.

IV. Transport Layer Multi-path

The next option for multi-connectivity, which we evaluate, is the MPTCP protocol. In the used configuration, data are transmitted concurrently on the available paths.

The following evaluation compares the throughput of single path TCP and MPTCP for the three different MNOs available in Germany. The measurement setup is equal to the one described in Sec. II. The measurements are taken in turns during each drive, one measurement with MPTCP, using all networks, and one measurement for each MNO. Taking measurements in turns avoids effects by weekday or time of day for which network utilization may vary, e.g. in busy hours. For probing of MPTCP the sending rate is increased to 360 MBit/s.

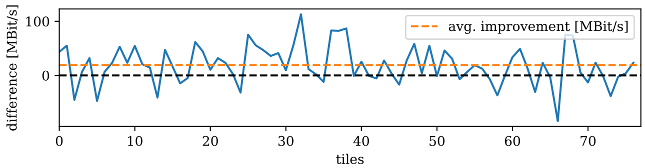

Fig. 6. Difference in throughput per tile for MPTCP with the congestion control algorithms Cubic and BBR configured. In most of the cases the congestion control algorithm BBR improves the throughput.

Fig. 5 illustrates the throughput of the MPTCP connection compared to the throughput achieved by the three individual connections and the sum of the three connections, respectively. The figure demonstrates that MPTCP improves the throughput in most cases. Still, the improvement is significantly below the sum of the three providers. In two cases the throughput of the MPTCP connection is below the throughput of the best MNO. Although the number of samples for each tile is sparse, it is observed that the MPTCP throughput is below the individual achievable data rate in all tiles. We infer from these results that MPTCP is not able to fully utilize the paths.

The reasons for a non optimal utilization is based on the interaction of the buffer sizes at the host, the queues in the network, the congestion control algorithm, and the MPTCP scheduler. For example, a non-loss based congestion control algorithm like BBR improves the throughput as shown in Fig. 6. We elaborate on this interaction in [9].

V. Related Work

Field measurements of multi-connectivity options in cellular networks are illustrated in [10]–[15].

The performance using MIMO antenna setups with up to eight antennas are evaluated in field measurements in [10]–[12]. All field trials indicate an improvement for MIMO setups in experimental LTE networks. We also verify such improvements in real-world commercial MNO networks. A field test for the MIMO performance in commercial networks is presented in [13]. The experiments are performed on trains, where LOS conditions are expected due to base stations close to the rails.

The authors in [14] evaluate the TCP and MPTCP performance. They focus on the effects during handovers in cellular networks. They demonstrate that the probability that a handover in different MNO networks occurs at the same time is about zero. They highlight the improved robustness if MPTCP is used, but they mention that the TCP throughput of the best MNO is typically higher than the aggregated throughput of MPTCP. The MPTCP and TCP throughput is compared in [15], too. The results in [15] include scenarios with low to high mobility and an aggregation of four MNO networks. The authors conclude that the throughput is improved compared to single-path TCP. Still, the results indicate room for improvement for MPTCP throughput.

VI. Conclusion

We evaluate the performance of multi-connectivity options in cellular networks for real-world vehicular scenarios. The first results we provide, compares SISO and MIMO antenna setups. We evaluate the application layer throughput, the RTTs and the reliability. The results show that the MIMO setup outperforms the SISO setup significantly. In our real-world track, the throughput increases by a factor of 1.72, which indicates that theoretical throughput gains are approached in the real-world. Improvements were observed even for conditions in which correlation between MIMO streams is expected, since measurements were mostly captured on a track that consists of highway segments in primarily rural areas. Regarding delay and packet loss, a MIMO antenna setup reduces both and, in addition, improves reliability with less network deregistration events. Nevertheless, since only one MNO is used, regions with poor network quality remain. The second performance evaluation we conduct evaluates MPTCP, a multi-path approach on the transport layer. We demonstrate an increase in throughput if multiple paths of different MNOs are aggregated, but also indicate that the aggregated throughput is below the sum of the throughput of individual MNOs.

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