MIMO Performance Evaluation of Automotive Qualified LTE Antennas

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***Abstract*—Future vehicles are expected to integrate multiple radio access technologies in order to support more efficiently traffic and infotainment applications. The focus of this paper is the performance evaluation of 3GPP Long Term Evolution (LTE) for automotive applications. The results presented are based on field measurements, which were carried out on a test track in Munich, Germany. The focus is the spectrum in 800 MHz, which is more challenging for multiple-input multiple-output (MIMO) antenna designs due to the difficulties of antenna decoupling. For the investigation an automotive qualified LTE MIMO antenna system is used. The presented results demonstrate that a performance deterioration of the antenna system occurs in areas close to the base station. It is shown that the deterioration is caused by shadowing between the two printed circuit board antennas comprising the antenna system. Moreover, it is illustrated that the signal-to-noise-plus-interference ratio (SINR), as opposed to the received signal strength indicator (RSSI), is a better suited parameter to determine the performance of the LTE link.**

***Index Terms*—Long Term Evolution; Automotive Antennas; MIMO; SINR, RSSI**

I. Introduction

In the near term, vehicles will be connected with each other and to the roadside infrastructure to provide traffic information services for Intelligent Transportation Systems (ITS). Several communication standards exist for vehicular communications to provide traffic information services for ITS. These communication standards include the vehicular-specific ETSI ITS-G5, an IEEE 802.11 derivative, and the 4G 3GPP communication standard LTE, offering increased bandwidth, scalability and largely reduced delay constraints. So far, only a few LTE performance investigations for vehicular antennas [1], [2], [3], [4] were published. All of the aforementioned publications focus on antenna configurations working either in the lower or upper part of the LTE spectrum. Thus being optimized only for one of these bands, no conclusion can be drawn with regards to the performance of an automotive qualified antenna system covering all relevant frequency bands.

In [1], the LTE performance was evaluated for roof top antennas with half a wavelength separation and a configuration, where in each side mirror an antenna was integrated. It was demonstrated that the roof top antenna configuration leads, in comparison to the antenna configuration in the mirror, to a diminished performance. However no conclusion was drawn explaining this behavior and a discussion if the parameters evaluated were the most suitable was not looked into either.

This publication is structured as follows; In Section II generic use cases being enablers for heterogeneous radio access technologies are discussed. Next, in Section III the measurement setup comprising the test track and the LTE MIMO prototype antenna are analyzed. The results obtained in the measurement campaign are studied in Section IV, illustrating methods to assess the LTE link performance and challenges in the antenna design. Finally, concluding remarks are drawn in Section V.

II. Use Cases for Heterogeneous Radio Access

The classes of use cases for heterogeneous radio access technology have different demands on the communication link. The performance requirements for the use cases discussed in this publication are distinguished into latency and throughput. Besides theses performance requirements, each application has requirements on the communication function, defining the message delivery service and the addressee. As message delivery service unicast, bi-directional communication, geocast and broadcast are distinguished. In unicast a transmission occurs in a particular direction, a connection does not need to be established e.g. beaconing applications, whereas bi-directional transmission require an active connection between the parties. In geocast the data is transmitted to multiple recipients in a certain region. In comparison to geocast no geographic limitation occurs in a broadcast transmission.

In the following different categorizations for a heterogeneous radio access technology, which can be found in the literature [5], [6], are discussed. In Figure 1 three categories: safety, backend and traffic information services, which according to their requirements have different demands on the communication link, are presented.

Safety use cases requiring short latency but low bandwidths include beaconing applications such as intersection assistance systems, as well as event driven applications such as collision avoidance systems. For beaconing based applications broadcast as well as unicast transmission can be used as message delivery system. Thus as well as cellular (LTE) and ad-hoc access technologies (ETSI ITS-G5) are available. The stringent latency demands typically require a vehicle-to-vehicle communication in contrast of using cellular systems. As cellular system have not originally been designed for ITS applications scalability investigations on live networks need to be pursued to determine how suitable they are for ITS safety applications.

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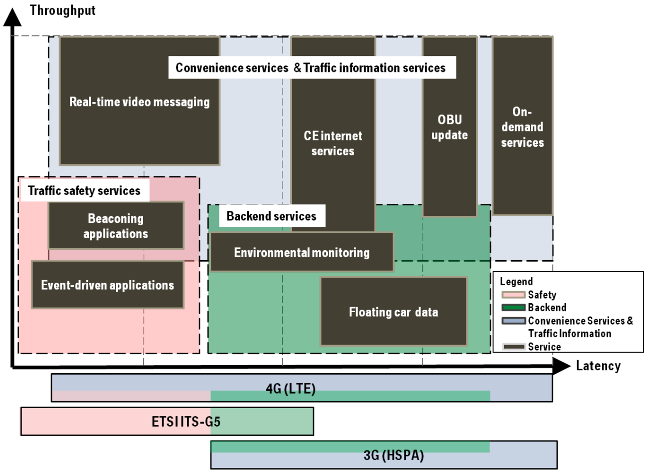


Fig. 1. Use cases for multiple radio access technologies in vehicles.

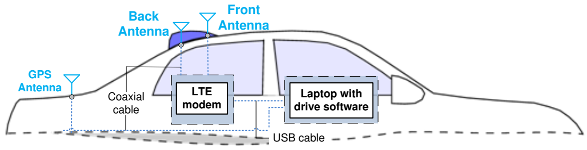


Fig. 2. Measurement setup.

Convenience and traffic information services do not have such stringent latency requirements as safety use cases, however their demands concerning latency and throughput are much more diverse and dependent on the running application. Moreover particular applications like real-time video messaging rely upon both short latency and high throughput. Services, however, as CE Internet services, on-board unit (OBU) update or on-demand services can potentially require high data rates but do not have stringent latency demands. Both cellular and ad-hoc access technology can satisfy these demands. However the limiting factor concerning the use of cellular systems would be the transmission cost. The communication would in both cases be bi-directional.

Backend services including applications such as environmental monitoring, where information gathered of the surrounding is processed in the backend and transmitted back to the vehicle as well as extended floating car data on, for instance, the current traffic information. Messages for applications like environmental monitoring which are triggered periodically are usually delivered in unicast. These use cases can be viewed as best effort traffic having no stringent requirements towards latency but up to mid-level throughput demands.

The access networks ETSI ITS-G5, UMTS (HSPA) and LTE, are also depicted in Figure 1 according to their suitability for the aforementioned use cases. As illustrated and described LTE is potentially able to cover all three categories, safety [7], backend and traffic information services. Therefore the focus of this paper is the performance evaluation and characterization of the LTE link. However as pointed out for the use of LTE for all aforementioned applications scalability analysis is necessary to investigate the behavior in regards to the delay with multiple active users in the cell.

III. Measurement Setup

The measurements were carried out using a sedan type vehicle, where the LTE MIMO antenna was placed on the conventional mounting space on the vehicle rooftop, as illustrated in Figure 2. Both antennas were connected to the LTE modem using 3 m long cables having an attenuation of 1.5 dB. The radio frequency parameters such as SINR or throughput, alongside the GPS coordinates, were obtained with a drive test software.

A. Measurement Test Track

A 9 km long test track, cf. Figure 3 served by a 800 MHz base station was selected for the measurements. The test track is located along the base station, where a line of sight component is established to the investigated automotive antenna allowing to evaluate the impact in link performance caused by inter cell handover. The test track includes three different environments urban, suburban and rural to visualize the antenna performance under different conditions. In the following the measurement drive starting at point Petuelring and ending in Verdistrasse (see Figure 3) is denoted as Direction I and the return trip as Direction II.

B. Characteristics of the Prototype LTE Antenna

The design of a multi-standard automotive qualified antenna capable of Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and LTE in MIMO mode is especially challenging in the low frequency range, where 262 MHz of bandwidth needs to be covered by one antenna and 71 MHz (791 - 862 MHz) by both. The MIMO antenna system used for this investigation consists of two printed circuit board antennas, being mounted at 90° on a FR-4 substrate, positioned in a PC-ABS casing on the vehicle rooftop. The feeding points of both the back and front antenna, cf. Figure 2, are aligned. The back antenna is covering the frequency bands of GSM at 900 MHz and UMTS at 2.1 GHz. The front antenna is only tuned to both LTE bands.The separation of both aligned antenna feeding points is 6 cm whereas the lowest spacing between the main and diversity antenna is 1.5 cm.

The return loss for the back antenna is in most relevant bands, LTE 800, GSM 1800, UMTS 2100 and LTE 2600 below -9 dB. A reference value for mobile phones, the automotive or most consumer electronic device industries is around -6 dB [8]. The highest return loss is seen at the end of the GSM 900 band, where a value of -8 dB is reached. A similar performance is observed for the front antenna, however the highest value of -8 dB for the return loss is seen at the end of the LTE 800 band.

The coupling loss, having a non-negligible impact on the MIMO performance, is ranging from -5.5 dB to -7 dB in the low frequency band at 800 MHz and is low as -18 dB in the

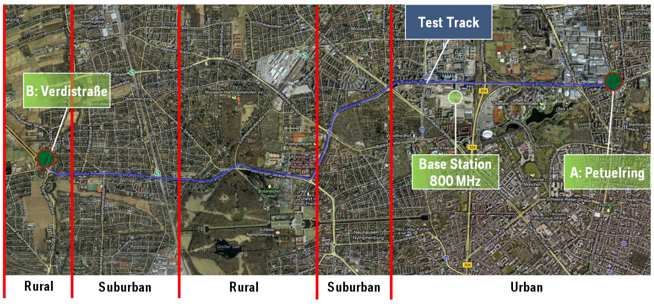


Fig. 3. The 9 km long test track used for the LTE 800 MHz measurements is leading across rural, suburban and urban environments in Munich, Germany.

higher LTE band at 2600 MHz. Thus the coupling between both antennas is only crucial at low frequencies. The other aforementioned bands are not considered for this parameter, since the antenna system is working in MIMO mode only in the LTE frequency bands. Alternatively to the coupling loss the near field s-parameter based antenna correlation indicates a correlation of 0.25 to 0.3 for the antenna system at the lower LTE band. According to the User Equipment (UE) radio transmission and reception for LTE release 8 [9] a channel correlation of 0.3 is considered to be medium for characterizing the MIMO performance.

IV. Measurement Results

In this section, the results obtained in the measurement campaign are presented and evaluated. The main focus is the characterization and assessment of the MIMO antenna system and the identification of the most relevant parameters to gauge the link quality for the use cases described in section II. The measurements were performed at 792 MHz, which is in the lower 800 MHz frequency spectrum rolled out in Germany. The base station of the network provider was limited to a data rate of 50 MBit/s in the downlink using a two antenna configuration and transmit power of 46 dBm.

In LTE, spatial multiplexing is only employed in the downlink, thus only the downlink is evaluated in this paper to assess the performance of the antenna system. Effects not controllable during the campaign such as altering server loads or longer shadowing periods due to the large vehicles, which both could falsify the findings, were circumvented by performing multiple measurement runs. To avoid cluttering of the measurement results due to long waiting periods at traffic lights or other unforeseeable incidents a spatial averaging of the results over a distance of 10 m, approx. twice the length of the vehicle, was performed. In order to ensure not falsifying the results for RSSI, SINR or throughput the averaging was only carried out, if the rank indicator did not change over the specified distance of 10 m. The rank indicator reveals the number of MIMO transmission layers that can be used in LTE.

A. Measurement Results for RSSI and SINR

A histogram of the RSSI distribution for the round trip is presented in Figure 4(a). The mean RSSI values for both antennas are similar for both directions; -63.5 dBm is measured for Direction I, whereas for the opposite route a value of -60 dBm is determined. The highest occurrence rates are found on Direction II in the range between -61 dBm and -64 dBm whereas for Direction I these are shifted to -80 dBm and around -83 dBm.

In Figure 4(b) the SINR is presented for the measurement performed for both directions, see measurement track in Figure 3. Even though the distribution of the bars in both plots differs from each other, the mean values for both routes is similar, around 17 dB. The variance, however, establishes the direction depending behavior of SINR, which subject to the route differs about 2 dB. Meanwhile even negative SINR values with an occurrence up to 1.5% are reached on the Direction I, only a few negative SINR values with a percentage below 0.15% are recorded on the return trip.

The most distinguishing characteristic comparing RSSI and SINR distribution is the resulting variance. Depending on the direction the variance can be as high as 6.4 dB for SINR, whereas the value for RSSI reaches values as high as 15.2 dB.

The impact of the direction chosen on the test track is also evident in the throughput distribution presented in Figure 4(c), where a shift towards lower throughput values is observed for Direction I. The return trip, Direction II, illustrates less spread data rates, which according to table I leads to a 4 MBit/s lower variance. The mean throughput value is similar for both directions, however data rates up to 50 MBit/s are only reached on Direction I.

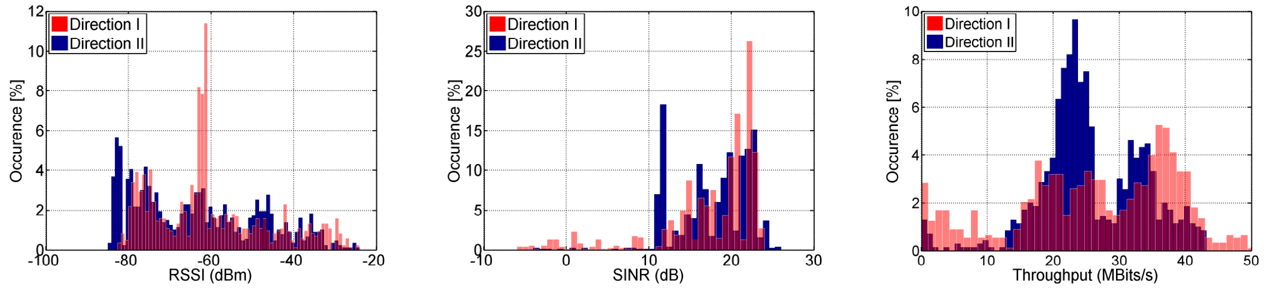
	Direction II		Direction I	
	mean	var.	mean	var.
RSSI [dBm]	-63.5	15.2	-60	13.9
SINR [dB]	17.8	4.5	17.3	6.4
Throughput [Mbit/s]	25.6	7.9	26.3	12.3

TABLE I
Mean and variance values for RSSI, SINR and for throughput dependent on the chosen route.

B. Throughput Scatter

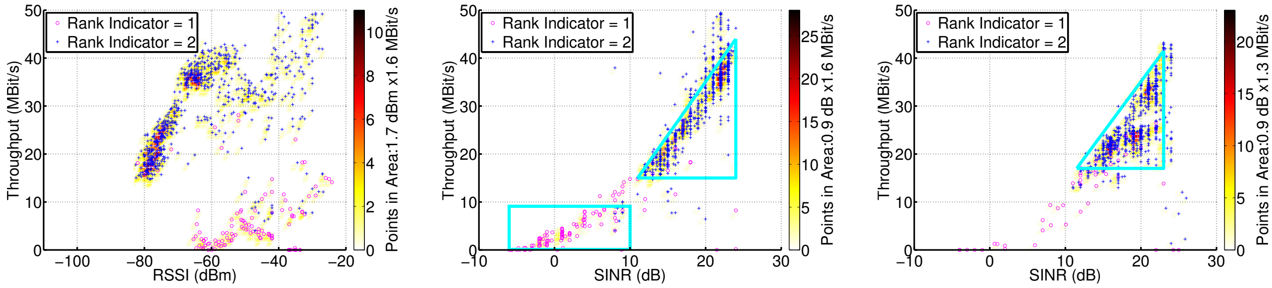
Comparing the scatter plots for RSSI in Figure 5 and for SINR in Figure 5(a) illustrates that SINR values offer an adequate relation to the throughput rather than RSSI. The highlighting, corresponding to the quantity of data points in a rectangle of the size specified at the colorbar, is used here to disclose areas with a high concentration of measurement points.

The scatter plot of RSSI versus the throughput, Figure 5(a), as illustrated here for Direction I, demonstrates only a relation between both parameters for a certain range, here between -80 dBm and -60 dBm. Besides this range no relation can be seen between the parameters. The SINR displayed in Figure 5(b) and 5(c), however, shows for both directions, in a first approximation, a linear relation to the throughput. For both cases the threshold for SINR has a value of 24 dB. The conclusion that SINR rather than RSSI is a more suited parameter to gauge the link performance is also established in [10]. In [10] it is established that SINR based vertical handoff algorithms offers the highest throughput under any noise level compared to power based algorithms.



(a) Mean RSSI distribution. (b) Mean SINR distribution. (c) Throughput histogram of both directions.

Fig. 4. Histogram of the mean SINR and RSSI of the front and back antenna as well as the throughput for the entire measurement track.



(a) RSSI distribution for 'Direction I'. (b) SINR distribution for 'Direction I'. (c) SINR distribution for 'Direction II'.

Fig. 5. Histogram of the throughput and scatter plots for the mean RSSI and SINR values for the entire measurement track.

The performance degradation of the MIMO antenna system, which was also seen in the previously discussed histograms is evident in both the RSSI as well the SINR scatter plot. The yielded results show that the lower throughput values are obtained when the rank indicator is one, thus establishing that a diversity instead of a spatial multiplexing transmission is employed. This behavior, however occurs predominantly for Direction I in particular between RSSI values of -65 dBm and -30 dBm and SINR values ranging from -5 dB to 10 dB in the marked area.

C. Geographic visualization of the Rank Indicator

To determine, if the performance deterioration is occurring in a certain area the rank indicator was analyzed for the entire measurement track. The results demonstrated that the LTE modem switched to rank indicator one, thus diversity transmission in the downlink, when driving close by the base station. Thus only this part of the 9 km long measurement track is shown in Figure 7. The LTE modem switches to rank indicator one, thus diversity transmission in the downlink, when driving close to the base station. Even though both lanes of the round trip are not that apart the diversity transmission mainly occurs for Direction I whereas spatial multiplexing is predominantly employed on the opposite direction.

D. Antenna Radiation Pattern

The direction dependent performance deterioration of the antenna system in the vicinity of the LTE base station is resulting from the gain difference of the MIMO antennas. The radiation pattern presented here is averaged between $0°$ and $10°$ in elevation. According to the pattern the gain of the front antenna is changing between 0 and -8 dBi, whereas the gain of the back antenna is altering between 2 and -9 dBi. The gain difference between both antennas, however, is not larger than 7 dBi.

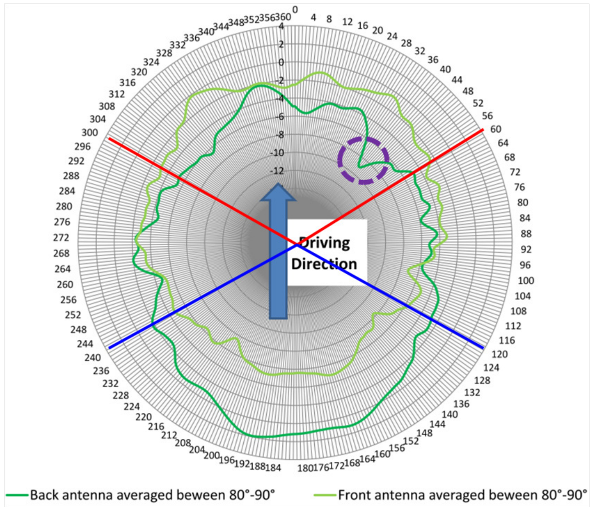


Fig. 6. Antenna radiation pattern of the LTE MIMO antenna system. The gain for both antennas is averaged between $0°$ and $10°$ in elevation.

The LTE modem switches to diversity transmission on Direction I, Figure 7(b), when either the difference in gain is 7 dBi or the gain of the front antenna drops below -6 dBi, which occurs at $44°$ and around $124°$ in azimuth. The impact in gain difference is more severe for the opposite route, Figure 7(a), where the radiation pattern of the front antenna, due to the closely spaced antennas, exhibits a deteriorated pattern up to 240° in azimuth. Thus, although, the gain of the back antenna applies up to 2 dBi the antenna system stays in diversity mode until 1 km past the base station. The averaged gain, between 300° and 60,$^\circ$, for Direction I results in 5.7 dB, whereas for Direction II the average gain, 120° and 240°, is 3.2 dB.

The imbalance seen in the radiation pattern results from the antennas being not separated enough. The resulting shadowing effects the MIMO performance more severely, as shown, in areas close to the base station.

E. Latency of the Link

The end-to-end latency measurements performed showed an average value of 55 ms. However in areas close to the base station, where low data rates were determined, a latency up to 2 s was measured. Taking in consideration the average latency the demands of safety as well as infotainment applications according to [5] and [6], are met. Due to performing the measurements under single user conditions further investigation on scalability and the resulting impact on the latency are however necessary.

(a) Test Track: 'Direction I'.

(b) Test Track: 'Direction II'.

Fig. 7. Rank indicator results for a section of the measurement track.

V. Conclusion

Future infotainment, traffic efficiency and safety applications rely on vehicles connected to the infrastructure and to one another by multiple radio access technologies. In this paper selected results of a measurement campaign carried out in the LTE 800 MHz frequency spectrum were presented to demonstrate the suitability of LTE for heterogeneous radio access use cases. The measurement track was chosen to evaluate the cellular performance under different environmental conditions.

Difficulties in the antenna design, especially with regards to the radiation pattern of the MIMO antenna system were established. Shadowing between the antennas, causing a diminished performance, were determined to be most severe in areas close to the base station. It was pointed out that such effects can be circumvented by misaligning the feed point of both antennas to obtain a radiation pattern being more congruent and closer to an omnidirectional antenna characteristic.

A method to improve the MIMO performance would be enlarging the distance between the antennas, mounting both antennas at different angles to the substrate or to misalign the feeding points.

Moreover it was established that SINR is a well suited parameter to evaluate the performance of the current network link. Power based parameters such as the RSSI proved to be inapt for characterizing the network link, since not offering a direct relationship to the throughput. However both parameters proved to be suited to determine, if diversity transmission was employed. Considering heterogeneous radio access the RSSI value is however necessary to determine if an alternate, better radio link compared to the current is available.

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