Evaluating Automotive Antennas for Cellular Radio Communications

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***Abstract*—Cellular connectivity plays an important role for the future development of automated and connected driving and intelligent traffic. An internet connection based on a 5G network can offer new services as entertainment (media streaming) or traffic information for improved navigation and cruising. Development and testing automotive antenna designs is time consuming and expensive. An open question is the evaluation of different antennas within a realistic environment. To fill this gap and facilitate optimal antenna design we introduce three scoring indicators to compare automotive antennas for cellular mobile communications and estimate their performance. This approach can be applied both to measured data and simulation results. The indicators help to make decisions on the type of integrated antenna by considering throughput as well as network coverage.**

***Index Terms*—Connected Car, Antenna, Ray tracing, Propagation, Measurement, V2X, V2I, Key Performance Indicator**

I. INTRODUCTION

Connected vehicles are expected to provide a stable internet connection through cellular networks such as Long Term Evolution (LTE) and Fifth Generation (5G) mobile communication. This internet connection will serve as a gateway to receive important service information such s traffic warnings and routing instructions for reaching a target destination safely and comfortably. On the other side, the ongoing transition to cloud-based media storage will lead passengers inside a car to increasingly access streaming content [1]. Both applications impose different requirements on the radio link: Service information requires a reliable connection and has to be available in highly diverse environments such as urban and rural areas. Streaming content often requires a high throughput, while video services are requested preferably on long trips along highways.

Car manufactures have been intensively working on integrating antennas into vehicles, to serve the need of coverage and throughput for the multi-band standards [2][3]. The limited possibilities for designing and placing antennas on a car lead to new challenges. To tackle this problem, we introduce a novel approach to score antennas. The scoring can be applied to measurement samples from field trials as well as to the results of numerical simulations. While measured data lead to more realistic samples, antenna scoring applied to simulation data enables an inexpensive way of developing and testing new antenna designs and locations on the car.

The paper is structured as follows: Section II specifies the different requirements of automotive antennas. Section III introduces the antenna scoring factors. To demonstrate the possibilities on investigating antennas, we set up a simple scenario described in Section IV. The results for three different antennas are compared in Section V.

II. PERFORMANCE SPECIFICATIONS

The performance of an automotive antenna that uses a cellular network for different applications depends on theses basic considerations:

1) Base station locations of the mobile operator
2) Static environment (e.g. surrounding buildings and vegetation)
3) Moving obstacles (e.g. surrounding vehicular traffic)
4) Network load in the currently connected cell (available radio resources)
5) Network load in neighbouring cells (received interference)

These parameters can be split into two groups: Antenna locations (1), including general information like the mounting height of the base station antennas as well as the size and density of radio cells, and the environment (2) are nearly static. in contrast, moving obstacles (3) and network load in the connected cell (4) as well as in neighbouring cells (5) depend on the time of the day and are classified as dynamic parameters. Both static and dynamic parameters affect the Reference Signal Received Power (RSRP) and Signal-to-Interference-plus-Noise Ratio (SINR) which are important Key Performance Indicators (KPIs) to evaluate the link quality: The propagation channel between a base station antenna and an automotive terminal antenna determines the RSRP. To establish a data transmission at all, a minimum RSRP satisfying the receiver sensitivity must be achieved. However, the SINR that is linked to the data throughput is essential to analyse an ongoing data transmission. High data throughputs require a high SINR while a minimum SINR of e.g. -6.48 dB for LTE must be guaranteed to transmit any data with respect to the available Modulation and Coding Scheme (MCS) [4].

Road traffic applications pose different requirements on the radio channel. The proposed antenna scoring targets to reflect the 'Throughput' and 'Coverage' capabilities of an antenna. For coverage-oriented applications it is important having a stable connection at all times, whereas throughput oriented applications require a high average throughput but do not rely on constant connection.

III. ANTENNA SCORING INDICATORS

The performance of a car mounted antenna can vary significantly. While a roof mounted antenna may reveal a favourable omni-directional pattern, antennas placed in the bumpers display a pronounced directivity. A roof mounted antenna will sense more cells at a time with less received power compared to directive antennas. Those can outperform an omni-directional antenna when facing towards the connected cell but performs worse if averted from the connected cell. For these reasons the received power level of directive antennas depends much more strongly on the base station location and the direction of driving compared to omni-directional antennas. It is therefore important to score antennas in a realistic scenario, either while performing a measurement campaign or by simulating the received power, e.g., using ray optical path loss predictions.

To compare omnidirectional and directional antennas we define the three important performance indicators Coverage Indicator (CI), Power Indicator (PI) and Throughput Indicator (TI) that can be combined into a single Antenna Scoring Indicator (ASI). We apply the scoring based on Grid Squares (GSs) with each square holding a group of samples.

A. Grid Squares

A measurement campaign conducted over a fixed time interval leads to a sample density varying along the track. More samples will be recorded when stopping at an intersection than doing to a drive on a road with high speed. When repeating measurements on exactly the same track, the varying traffic flow will cause different sizes and positions of available samples. Additionally, inaccuracies from the location estimation of Global Navigation Satellite Systems (GNSS) might lead to data points scattered around the track. In the proposed scoring method this problem is solved by using Grid Squares (GSs) to allow for comparing antennas from different sets of test drives along the same track.

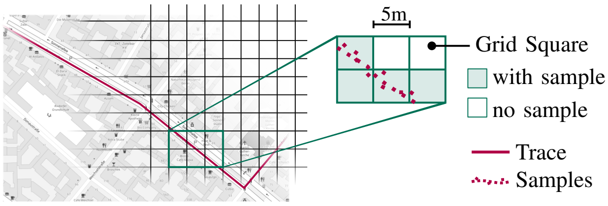

Fig. 1. The geographical map is overlaid with a grid of fixed cell size. Samples inside one grid square are grouped together to mediate the problem of a varying sample density.

The geographical map is overlaid with a grid with a fixed cell size of $5 \cdot 5$ m^2 as shown in Figure 1. Measurement samples located in one GS are grouped together and represent a grid area of 25 m^2. This approach makes it possible to calculate the Grid Power (GP) introduced in Section III-B along a track with varying sample density as well as GNSS inaccuracy.

B. Coverage Indicator

Let there be k_i samples located inside a GS i, the Grid Power (GP) of the GS i is then defined as the mean value

$$GP_i = \frac{1}{k_i} \cdot \sum_{m=0}^{k_i} p_{m,i}$$

with the power value p of sample m. The Coverage Indicator (CI) of an antenna for an area of interest containing n GSs is then defined as

$$CI = \frac{1}{\gamma} \sum_{i=0}^{n} (e_i \cdot A_{\mathrm{GS}_i}) \text{ with } e_i = \begin{cases} 1, \text{ if } GP_i \geq RX_{\mathrm{min}} \\ 0 \text{ , else} \end{cases}$$

with grid area $\mathrm{A_{GS}}$. γ is used to normalize all indicators along the driven track. It sums up the effective number of GSs passed across and is defined as follows:

$$\gamma = \sum_{i=0}^{n} (g_i \cdot A_{\mathrm{GS}_i}) \text{ with } g_i = \begin{cases} 1, \text{ if } GP_i > 0 \text{ mW} \\ 0 \text{ , else} \end{cases} .$$

The CI represents an area with an averaged received power greater than or equal to the threshold value $\mathrm{RX_{min}}$ while $\mathrm{RX_{min}}$ should be set according to the respected receiver sensitivity. The CI represents the fractional area at which a connection to the base station is possible. The greater the value of CI, the higher will be the probability that the corresponding antenna can be successfully employed for data transmission.

C. Power Indicator

The Power Indicator (PI) of an antenna is defined as

$$\mathrm{PI} = \frac{1}{\gamma} \sum_{i=0}^{n} \left(\mathrm{GP}_i \cdot A_{\mathrm{GS}_i}\right)$$

with the total number of GSs n and the normalizing factor γ as defined before. This indicator quantifies the total received power but neglects if a connection to a base station is possible.

D. Throughput Indicator

The Throughput Indicator (TI) of an antenna is defined as

$$TI = \frac{1}{\gamma} \sum_{i=0}^{n} \left(s_i \cdot A_{\mathrm{GS}_i}\right) \text{ with } s_i = f\left(\frac{GP_i}{I+N}\right).$$

The spectral efficiency s of the ith GS is a function of SINR with interference power I and noise power N. f is a suitable function that maps SINR to throughput. In our study, we used a step function of LTE to map the SINR to an MCS [4][5]. The interference power is strongly time variant. For test drives, the TI considers the measured SINR for each sample. In our example simulation we assumed a constant interference power along the whole evaluation tack. The TI indicates the overall throughput for an antenna along the track. It can be calculated at different interference levels for comparing antenna performance under different cell load conditions.

E. Metric Discussion

The parameters CI, PI and TI indicate different properties, thus making it possible to estimate the antenna performance for different applications. A high CI-value promises a good coverage but makes no decision on the link quality, whereas a strong PI indicates a good throughput in case a connection is possible. Moreover, the PI can be used in case if no suitable spectral efficiency mapping function is available as needed for deriving the TI. The throughput indicator is a trade-off putting coverage and power into relation. To allow car manufactures to consider the target field of application in the development process of an antenna, an Antenna Scoring Indicator (ASI) combining the weighted sum of CI, PI and TI can be used:

$$ASI = a \cdot CI + b \cdot PI + c \cdot TI$$

The weighting factors a, b, and c have to be set according to the needs of the intended automotive application.

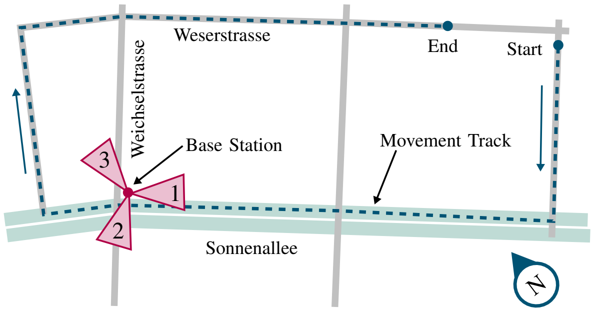

Fig. 2. Simulation scenario in the city of Berlin. The three-sector base station (red colour) is located at the intersection Sonnenalle/Weichselstrasse. The blue dashed line indicates the movement track, surrounding the base station.

IV. EXEMPLARY SIMULATION

To demonstrate the scoring of antennas, we set up a simple scenario inside the Simulator for Mobile Networks (SiMoNe) environment developed at the Institute for Communications Technology at the Technische Universität Braunschweig [6]. The scenario is shown in Figure 2. The path loss was calculated ray optically considering 1st and 2nd order reflections as well as diffraction at the edge of building for a time resolution of 100 ms. Because of its publically available 3D building data [7], simulations were performed for a sector within the city of Berlin, by placing a single base station on the intersection Sonnenallee/Weichselstraße. One vehicle equipped with different antennas surrounded the base station in 2:50 minutes considering all known traffic rules but without consideration of other road users. The simulation did not contain any localisation inaccuracy as described in Section III, but the modelled track, marked by the dashed line, was effected by a varying sample density because of acceleration and deceleration at intersections.

We equipped the base station with a typical Kathrein antenna operating at the frequencies 900 MHz, 1800 MHz and 2400 MHz. We then considered three automotive antennas: Antenna 1 is a roof antenna mounted on the front center as published in [8]. Antenna 2 is a roof integrated antenna as described in [9]. Because of their nearly omni-directional pattern across the upper hemisphere, these antennas are termed 'Omni 1' and 'Omni 2', respectively, in the following. To compare the performance of these omni-directional patterns with a directive one, we chose a horn antenna [10] as a third antenna, termed 'Directional', with its 3D antenna gain pattern measured at TU Vienna. It should be noted here that, in contrast to the omni-directional antennas any influence from the metallic roof was neglected. In simulation, the horn antenna was placed on the roof center facing towards the direction of driving. The three

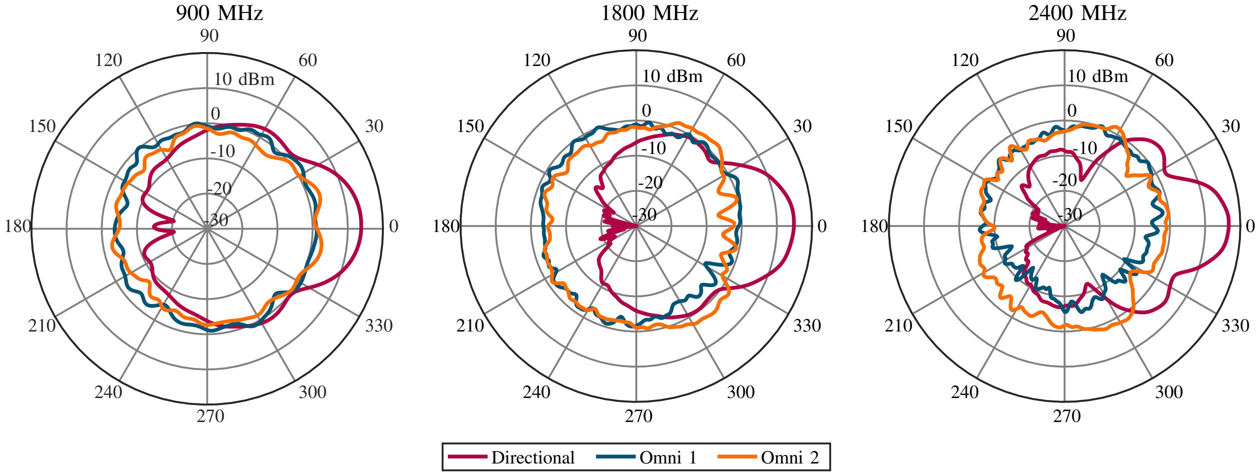

Fig. 3. Horizontal cut of the antenna gain patterns at an elevation angle $\Theta = 15°$ above horizon for 900 MHz (left), 1800 MHz (center) and 2400 MHz (right). Azimuth $\Phi = 0°$ is facing towards the front of the car.

antenna gain patterns are shown in Figure 3 for the frequencies of 1800 MHz and 2400 MHz.

V. RESULTS

Based on these considerations, we studied the three performance indicators TI, PI and CI. The results are shown in Figure 4. The CI and TI shown here were computed separately for the three base station sector-antennas with a fixed interference plus noise power of -100 dBm. As expected, the omnidirectional antennas perform similarly. However, coverage and throughput are slightly better for antenna 'Omni 2'. On the other side, the TI of the directive antenna offers the worst coverage and throughput performance for all frequencies and sector-antennas, although a better PI for a few of the sector-antennas.

A mobile device typically performs an handover to the base station offering the best radio link. We therefore computed the CI and TI for the whole track assuming the mobile antenna always connected to the best serving base station antenna. The results are summarized in Table I for two fixed interference plus noise power values (stated as 'I+N') of -100 dBm and -60 dBm. As expected, the omnidirectional antennas perform better in terms of throughput at low I+N levels, as they offer a favourable gain independent of the orientation of the car with respect to the base station. At high interference levels, the gain of the directional antenna is able to keep a high throughput. E.g. the directional antenna offers a 57 % throughput increase at 1800MHz compared to the omni-directional antennas. However, specifically in an urban environment as evaluated here, a directive antenna would not always be oriented towards the base station.

The results for this simple urban scenario motivate further research on designing state-of-the-art antennas

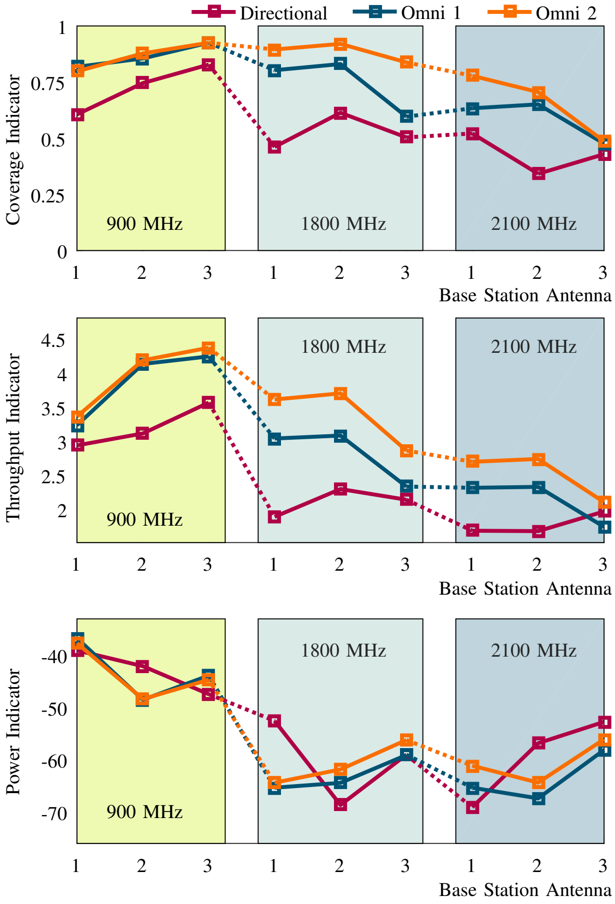

Fig. 4. Variation of the performance indicators CI (top), TI (center), PI (bottom) for the three sectors of the base-station antenna as indicated in Fig. 3, for all three automotive antennas (different colors) at the three frequency ranges indicated. The interference power plus noise power was set to at a fixed level of -100 dBm for a receiver sensitivity of -98 dBm.

with omnidirectional patterns. Furthermore, pattern reconfigurable and beam steering antennas could offer throughput as well as coverage regardless of the interference level [11].

TABLE I
THROUGHPUT AND COVERAGE INDEX ASSUMING BEST SERVER CELL SELECTION

I+N	Ant.	Index	900 MHz	1800 MHz	2100 MHz
-100 dBm	Direc.	CI	0.93	0.66	0.53
		TI	4.3	3.02	2.45
	Omni 1	CI	1.0	0.99	0.93
		TI	5.49	4.32	3.52
	Omni 2	CI	1.0	1.0	0.95
		TI	5.54	5.05	4.01
-60 dBm	Direc.	TI	1.54	0.55	0.35
	Omni 1	TI	1.33	0.35	0.22
	Omni 2	TI	1.39	0.38	0.32

VI. CONCLUSION AND OUTLOOK

We have introduced a set of antenna scoring metrics that allow for comparison of different antennas with regard to cellular coverage and throughput. The indicators can be used to score automotive antennas in realistic scenarios to make decisions on the performance for different use cases and channel conditions. The metric is based on power samples that can be obtained from measurement and/or simulation. We studied the performance on the basis of a simple simulation scenario in the city of Berlin and applied the scoring to three different realistic antennas. In this setup the two omni-directional antennas seem to offer better results in terms of coverage and throughput as compared with the directional antenna, while the directive antenna offers better throughput in networks with high interference level.

In this study we used a fixed interference power level to evaluate the throughput performance of an antenna. As a next step, we plan to apply this metric on a long track across a city considering a complete realistic cellular network with a multitude of base stations. Such scenario will be able to investigate the effect of dynamic interference. Moreover, antennas needs be evaluated regarding the environment. The cellular network structure along a highway, with its two-sector base stations facing the track, differs significantly from an urban environment. Therefore, it is an open question which type of antennas, directive or omni-directional, are better suited regarding the environment.

REFERENCES

[1] G. Pau, “Quickly home please: How connected vehicles are revolutionizing road transportation,” *IEEE Internet Computing*, vol. 17, no. 1, pp. 80–83, Jan 2013.

[2] H. Lind, “How new active safety systems and always connected vehicles leads to challenges on antenna design and integration in the automotive domain,” in *2013 7th European Conference on Antennas and Propagation (EuCAP)*, April 2013, pp. 3–4.

[3] B. Sanz-Izquierdo and R. Leelaratne, “Evaluation of wideband lte antenna configurations for vehicle applications,” in *2013 Loughborough Antennas Propagation Conference (LAPC)*, Nov 2013, pp. 383–387.

[4] ETSI TS 136 213, *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures*, ETSI Std., 2017.

[5] Qualcomm Europe, *R1-081483; Conveying MCS and TB size via PDCCH*, 3GPP TSG-RAN WG1 Std., 2012.

[6] D. Rose, J. Baumgarten, S. Hahn, and T. Kürner, “SiMoNe - Simulator for Mobile Networks: System-Level Simulations in the Context of Realistic Scenarios,” in *81st IEEE Vehicular Technology Conference (VTC Spring 2015)*, May 2015.

[7] Berlin open data. [Online]. Available: https://daten.berlin.de/

[8] M. E. Asghar, F. Wollenschläger, A. Asgharzadeh, J. Singh, and M. A. Hein, “Influence of antenna mounting location on the radiation pattern of an automotive antenna,” in *12th European Conference on Antennas and Propagation (EuCAP 2018)*, April 2018, pp. 1–5.

[9] G. Artner, W. Kotterman, G. D. Galdo, and M. A. Hein, “Conformal automotive roof-top antenna cavity with increased coverage to vulnerable road users,” *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 12, pp. 2399–2403, Dec 2018.

[10] NSI, *WR975 Standard Gain Horn*.

[11] G. Artner, J. Kowalewski, J. Atuegwu, C. F. Mecklenbräuker, and T. Zwick, “Electronically Steerable Parasitic Array Radiator Flush-Mounted for Automotive LTE,” in *13th European Conference on Antennas and Propagation (EuCAP 2019)*, April 2019.