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Enhancing cellular vehicular uplink performance: experimental evaluation of switching antenna system

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***Abstract*—Cellular networks will be one of the main pillars in the development of future vehicular communications. However, downlink (DL) and uplink (UL) channels must be improved to cope with the required reliability and high throughput of the coming vehicular use cases. Vehicle side solutions which benefit from the high antenna gains could improve the performance of the UL channel whose coverage is limited by UL transmit power. In this paper we experimentally evaluate the performance of a directional antennas switching system based on live Long Term Evolution (LTE) measurements. A total of more than 150 km have been driven comprising different radio propagation scenarios. The results show considerable improvements of Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ), together with a reduction of handovers specially in scenarios with high Line-Of-Sight probability. Additionally, it has been found that the UL throughput does not improve with the increase of antenna gain probably due to the UL Power Control mechanism used in LTE.**

I. INTRODUCTION

Future vehicular communication systems will be required to deal with high Uplink (UL) and Downlink (DL) data rate demands together with reliable connectivity. Cooperative sensing and awareness, teleoperated driving or infotainment are some examples in which the required UL throughput can reach up to 25 Mbps [1].

The next 5th Generation (5G) radio technology is expected to cope with a plethora of services with diverse requirements, including vehicular communication [2], [3]. Previous studies have proposed the use of Base Station (BS) adaptive beamforming in sub-6 GHz bands [4] and the exploitation of the millimeter wave spectrum [5] to increase the system throughput. However, their practical deployment is subjected to the computation complexity of the Angle of Arrival (AoA) and the reduction of range with the increase of frequency. This could be counteracted by the massive deployment of Road Site Units which would improve the coverage and throughput at the cost of increased number of handovers, latency and cost-inefficiency if deployed in low-populated areas. The use of Vehicle to Vehicle (V2V) communications by means of using surrounding vehicles as relays in order to leverage better channel conditions is proposed in [6]. Nevertheless, its performance is considerably affected in scenarios with low density of vehicles or in congested systems.

Long Term Evolution (LTE) is another suitable system whose already deployed infrastructure, scalability and ubiquitous accessibility make it a potential candidate to serve the vehicular use cases. This technology is also well-suited to experimentally study potential solutions which would be later applicable in future 5G networks. Authors in [7] have shown the coverage challenge in vehicular scenarios through Reference Signal Received Power (RSRP) measurements. The presented results demonstrate insufficient range for many vehicle data applications. Besides that, UL coverage is even more critical due to the limited UL transmit power.

Alternative solutions applied from the vehicle side become attractive for car vendors due to their possible implementation without standardization. In [8], authors have shown the potential DL Signal to Interference and Noise Ratio (SINR) gains of using receive beamforming on the vehicle side. However, receive beamforming requires expensive and synchronized hardware equipment in addition to high computational complexity of AoA estimation. The use of directional antennas at the vehicles is a well-known [9] alternative to beamforming. Its implementation is much simpler though it presents limitations of the available pointing directions. Although previous approaches have considered the theoretical potential of this solution, upcoming high throughput vehicular use cases claim for the experimental evaluation of its performance.

In this work we experimentally evaluate the use of a switched-based system of directional antennas on the vehicle terminal in both UL and DL. We compare the performance of the switching antenna system with a benchmark case of omni-directional antenna configuration. We conduct measurements of RSRP and Reference Signal Received Quality (RSRQ) by the vehicle terminal in live LTE networks. The measurements include a wide variety of different radio propagation scenarios where the solution could be deployed. Furthermore, we investigate the impact of the antenna gain over the UL throughput and the Handovers (HOs) performance.

The reminder of this paper is structured as follows: Section II describes the measurement equipment and the antenna switching methodology. The campaign itself is described in Section III. Section IV compares the results of the directional and omni-directional antennas systems analyzing the signal strength and quality, UL throughput and the mobility performance. Then, Section V discusses main findings. Finally, Section VI concludes the paper.

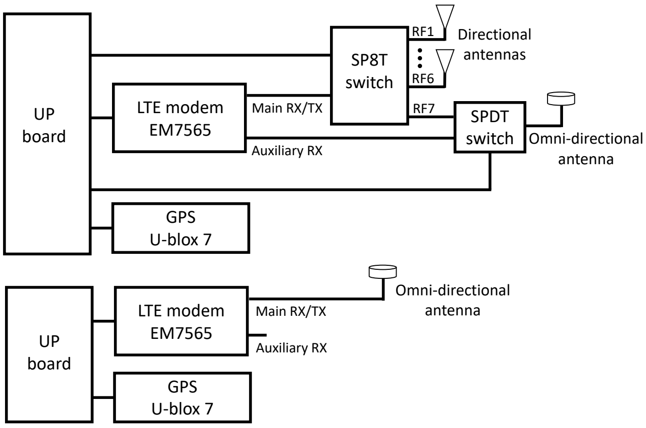

Fig. 1: Measurement equipment setups for the directional (top) and omni-directional (bottom) antennas configurations

Fig. 2: A measurement vehicle with the antenna structure on the roof

II. Measurement Methodology

A. Measurement equipment

The measurement equipment consists of a switching antenna system with six directional antennas connected to a LTE modem through a Single Pole, 8 Throw (SP8T) Radio Frequency (RF) switch. The system is controlled by an embedded computer which interacts with the LTE modem, RF switches and a Global Positioning System (GPS) receiver. For comparison purposes, a second system is used consisting of an omni-directional antenna attached directly to the second LTE modem. Both systems as shown on Figure 1 are independent from each other. The antennas of both systems are mounted on the roof of a van as shown on Figure 2.

Antennas

Six *SENCITY Spot-S Railway Cellular* directional antennas are used. They have 8 dBi of peak gain at the target frequency 1.8 GHz chosen as most densely deployed LTE band in Denmark. The 3 dB beamwidth of each antenna is 70°. As shown on Figure 3, the antennas are positioned on a roof of the vehicle following the hexagon pattern covering sectors of 60°. Please note that the discrepancy between the nominal 3 dB beamwidth and the width of the sector causes a desired overlap between sectors in case of the potential GPS inaccuracies.

In the second system, an omni-directional *SmartDisc* antenna with a 3.15 dBi gain is utilized. The same antenna model is also used as the supplementary receive diversity antenna in the directional system (Figure 1). Its purpose is described later in Section II-C. Directional antennas have 4.75 dB higher gain than the omni-directional antenna. This difference must be considered in the RSRP and RSRQ performance comparison.

LTE modem

The *AirPrime EM7565* LTE Cat-12 embedded cellular modem is utilized to provide LTE connectivity and measurement reports of the RSRP and RSRQ of the serving cell. It has one main RF port for DL/UL transmissions and one auxiliary RF port for enabling receive diversity. This downlink-only port, disabled in the omni-directional system as having no effect on the uplink, is used in the directional setup to improve the mobility performance of the modem as explained in the next Section. The modem is set to operate only in the LTE mode at band 3 (1.8 GHz).

RF Switches

Two RF switches are used in the system of directional antennas. The SP8T switch is used for selecting among the six directional antennas. Its input port is connected to the main RF port of the modem and its outputs to the six directional antennas and to the Single Pole, Double Throw (SPDT) switch. The purpose of of the SPDT switch is to interconnect the omni-directional antenna to the auxiliary RF port of the modem as a receive diversity antenna or through the SP8T switch to the main RF port where is used for the initial BS attachment procedure. This procedure will be further addressed in Section II-C.

Other modules

For the interaction between hardware modules an *UP board* is used as an embedded controller. Additionally, the *u-blox 7 GNSS* receiver obtains the geographical coordinates and orientation of the vehicle with 5 Hz update rate. These information are later used in the antenna selection process.

B. Antenna switching methodology

The antenna selection algorithm is based on the known GPS location of the serving BS and the position of the vehicle terminal. The selected antenna is the one which best points in the shortest geometrical direction towards the serving cell. The six antennas are divided in sectors of 60° which define the switching bounds between antennas. The real-time algorithm continuously obtains the serving Cell ID from the LTE modem. For every GPS update, it calculates the angle of the shortest path between BS and the vehicle accounting for its present

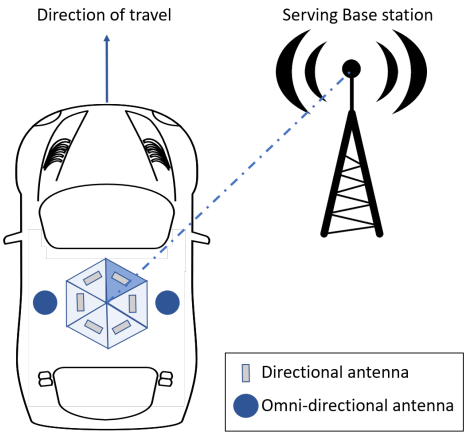

Fig. 3: Antenna selection with the 6 directional antennas

orientation (direction of travel). The angle is translated into the selection of one of the antenna sectors. Readers can refer to the example illustrated on Figure 3 to observe how the antenna is selected according to the vehicle orientation and location.

It can be observed that the knowledge of the BS's location is indispensable since without this information proposed methodology could not be applied and would have to be replaced by other techniques like periodic beam-sweeping or AoA estimation. The proposed method assumes that the strongest signal comes from the direct path between the vehicle terminal and the serving cell. This assumption is valid in Line-Of-Sight (LOS) scenarios predominant in rural and suburban scenarios. However when direct path is obstructed (None-Line-Of-Sight (NLOS) conditions, dominant in dense urban deployments), the strongest signal might come from a completely different direction. In these conditions, the performance of the proposed system could degrade. However as shown using ray-tracing simulations in [10], even in NLOS urban scenarios there can be a time-distance correlation of AoA usually still coming from angles similar to LoS.

C. *Initial cell attachment and mobility performance*

The use of directional-antennas can influence the initial cell attachment. At the start of the system, the modem has to acquire the LTE connection to the cell which presents the best radio link. Directional antennas might influence the initial attachment by means of the gain into the pointing direction. In a possible unlucky scenario, a modem initialized using a directional antenna in a given direction can attach to a suboptimal far-located cell even though there is a much stronger candidate in a different direction coinciding with the null of the chosen antenna beam pattern. To mitigate this potential suboptimal choice of the serving cell, in this work first the omni-directional antenna is connected to the main RF port of the modem and is used for the initial cell attachment. Only after acquiring the network connectivity, the antenna is switched and the directional one is used towards the direction of the serving cell.

TABLE I: Characteristics of the measured environment [8]

Route index	**Measurement environment**	**Short description**
Route 1	Dominant rural and suburban	Small houses and meadows, seldom deployed Base Stations (BS)
Route 2	Highway and urban	Blocks up to the 3rd floor in the urban part, medium density of BS
Route 3	Highway and dense urban	Blocks up to the 6rd floor, high density of BS
Route 4	Suburban	University buildings, high density of BS

Mobility management is another aspect influenced by using directional antennas. In cellular systems network triggers the HO decision based on the measurement reports from the modem. Using directional antenna would enhance/mitigate the measured neighbor signals power from some directions leading to changed mobility pattern. In some situations, as shown later in this work, it may be a desired behavior as a modem can longer remain connected to the same cell reducing the handover rate. However in some other situations it may downgrade the network performance as the modem would prolong the connection to a weak cell overlooking the more suitable one in the direction where antenna null is located. As a trade-off, in this work the omni-directional antenna used first for the initial attachment, is later connected to the modem's auxiliary RF port. In this way, using receive diversity mode, the modem in its measurement reports, report the best neighbor signal power received among two different antenna ports. In this situation the nulls of the directional antenna are mitigated, however its directionality behavior is preserved. Please note again, that the auxiliary RF port is downlink only and the omni-directional antenna does not influence the uplink studies of this work.

III. MEASUREMENT CAMPAIGN AND POST-PROCESSING

A. *Measurement campaign*

The measurement campaign was conducted in Aalborg, Denmark. Four routes with different radio propagation environments were driven as described in Table I. The driven roads comprise a total of more than 150 km and the speed of the vehicle varied from 0 km/h in urbanized areas up to 100 km/h in the highway. Readers can refer to [8] for further details on the driven routes. The LTE connectivity was provided by a Danish network operator whose BSs locations were known. While driving, omni-directional and directional antennas systems were simultaneously measuring RSRP and RSRQ metrics with 500 ms periodicity such that more than 16000 measurements were collected. In both systems, a continuous full-buffer UL transmission was carried out and UL throughput was measured by the controller.

B. *Post-processing*

Prior to the analysis, the recorded data is filtered in the post-processing. When a HO occurred, some instances of RSRP

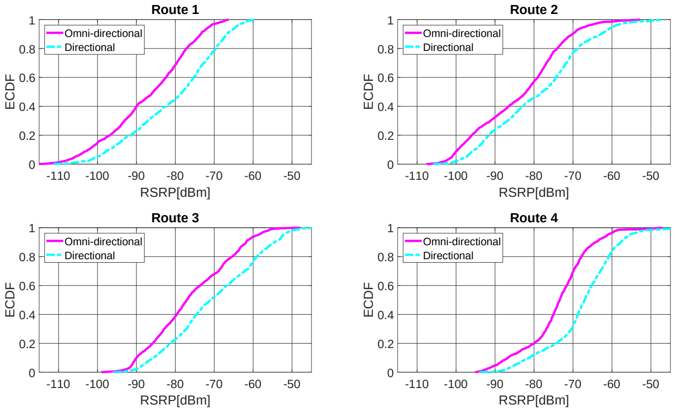

Fig. 4: ECDFs of the measured RSRP of the serving cell

and RSRQ were measured before the antenna was effectively switched towards the new BS location. These values have been filtered to ensure that the measured RSRP and RSRQ correspond to the time traces where the directional antenna was pointing into the desired direction. Additionally, the omni-directional and directional systems differ from signal attenuation introduced by the hardware modules between antennas and RF ports (see Figure 1). Since the RSRP is measured in the modem RF port, the reported values are altered. Hence the RSRP values have been compensated to include the impact of the antenna gain.

IV. RESULTS

A. *RSRP and RSRQ*

The following results comparing downlink RSRP and RSRQ for both systems are showed for the time instances in which both systems are connected to the same serving BS (more than 85% of snapshots). The Empirical Cumulative Distribution Functions (ECDFs) of the measured RSRP in the four driven routes are presented on Figure 4. A continuous gain on the measured RSRP by directional antennas with respect to the omni-directional case can be observed. This gain is slightly reduced in the more urbanized scenarios (Routes 2 and 3) due to higher probability of NLOS. The observed median gains in three routes are slightly higher than expected theoretical antenna gain difference (4.75 dB). This may be due to the constructive fast fading of the channel. The effects of the destructive fading, or the NLOS propagation are mitigated due to the use of an auxiliary omni-directional antenna in the directional system which observes independent channel due to physical separation from the directional system. In general, routes 3 and 4 present the largest RSRP values due to high density of BSs in these scenarios. Route 1 shows the lowest values due to longest distance to the serving BSs common in rural scenarios.

The signal quality enhancement can be assessed by means of the RSRQ. The ECDFs of the measured RSRQ are presented on Figure 5. With the use of directional antennas, the RSRQ experiences a constant gain over the omni-directional antenna case of approximately 1 dB. Hence, the directionality of the

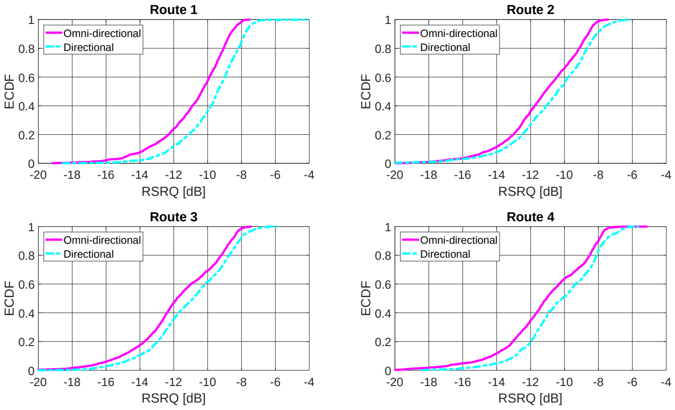

Fig. 5: ECDFs of the measured RSRQ of the serving cell

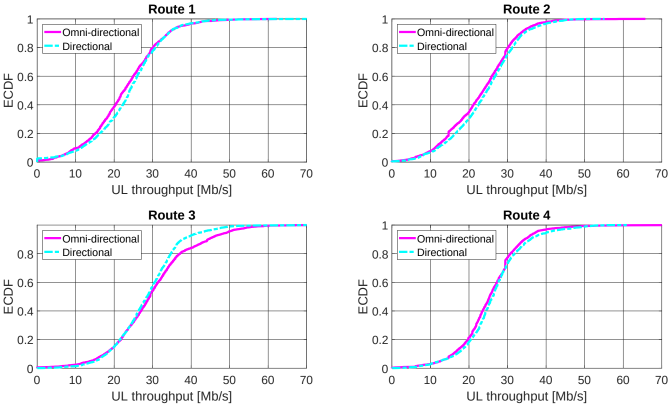

Fig. 6: ECDFs of the measured UL throughput of the serving cell

antennas not only improves the signal strength, but also the quality thanks to the attenuation of interfering signals coming from different directions than the serving BS.

B. *UL Throughput*

A full-buffer UL transmission let us assess the UL throughput performance. Although, in this work, the instantaneous cell load information was not accessible, due to the sufficient amount of samples, one can assume the similar average load and therefore fair comparison between both antenna systems. The ECDFs of the UL throughput in the different scenarios are shown on Figure 6. The observed plots show almost no UL throughput improvement with the use of directional antennas, which contradicts the experienced improvement of the DL channel by means of RSRP and RSRQ gains.

The UL throughput performance could be affected by the UL Power Control (PC). In LTE, the Open-loop UL PC scheme [11] is primarily used for compensating the channel Path-Loss (PL). As the network is not aware of the vehicle's antenna system, its directional gain is observed by the reduced PL and fully-compensated by UL transmit power reduction. Only in scenarios with high PL, the transmitted power can reach the maximum allowed value (23 dBm). In those conditions, the UL transmitted power remains constant and a

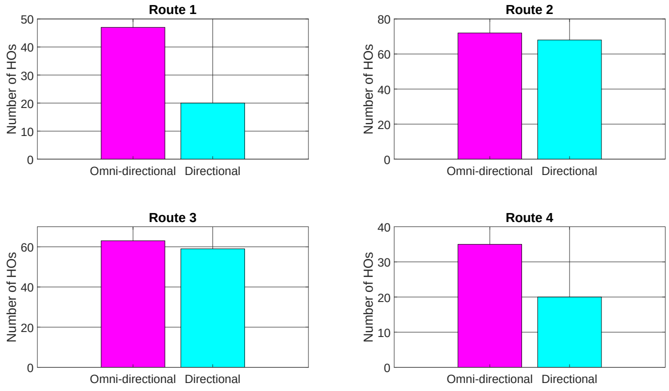

Fig. 7: Number of successful HOs

throughput gain should be observed. However, very high PL scenarios correspond to RSRP values much below -100 dBm which are barely experienced in our results.

C. *Mobility performance*

The measured values of RSRP are reported to the network to be used as inputs in the mobility management. The gains in RSRP indicate the improved radio link with serving BS for longer time and can potentially lead to the reduction of observed HOs resulting in lower latency and higher reliability as number of potential failed HOs or radio link failures would also be reduced. The number of performed HOs on each route is shown on Figure 7. A considerable reduction of HOs of 57.1% and 42.8% is observed in Routes 1 and 4 while almost no reduction is observed in Routes 2 and 3. This is explained by the higher probability of LOS links in Routes 1 and 4 leading to extended attachment to the same cell, whereas in Routes 2 and 3 (the urbanized environments) due to the BS density and NLOS propagation frequent HOs are still observed.

V. DISCUSSION

Directional antennas have shown a potential improvement in the DL communication with RSRP and RSRQ gains as well as HO reduction. As expected, higher gains/reduction is observed in the rural and suburban environments where directional systems are expected to be most beneficial. Despite lower gains and no handover reduction in the urban scenario, it is worth to recall that the uplink related coverage and reliability issues are not as harmful as in the rural scenarios as other network-side techniques may be used to eliminate the problem.

The UL throughput performance has experienced no improvement regardless the difference of the antenna gain. This finding is also valid in case any beamforming technique is used in place of directional antennas. It leads to the conclusion that without the network knowledge of the antenna system used by the vehicle, there will be no visible improvement for the car manufacturers of using an advanced antenna system. However, already today, if the network is aware of the problem, communication standards can enable the possibility to circumvent this issue. The so-called user specific closed-loop power control scheme can be used to differentiate users and avoid discounting the transmit power to those benefiting from high antenna gains [11].

VI. CONCLUSIONS

We have experimentally evaluated the performance of a directional antennas switching system implemented in the vehicle terminal. The DL performance has been analyzed with RSRP and RSRQ measurements. Comparing with an omni-directional antenna, directional antennas improved the RSRP in more than 4.75 dB (antenna gain difference) in LOS scenarios. The RSRQ was also improved with an average gain of 1 dB. The improvement of the mobility performance has been corroborated with a HOs reduction of almost 50 % in rural and suburban scenarios. In urbanized scenarios the reduction of HOs is insignificant due to NLOS situations. However, the enhancement of the DL metrics is not translated into an increase of the UL throughput. This is likely due to LTE power control mechanisms which aims at similar receive power levels for all the served UEs.

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