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On the potential of uplink beamforming in vehicular networks based on experimental measurements

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***Abstract*—This work evaluates the concept of uplink beamforming for vehicular communications in the sub-6 GHz frequency bands to improve throughput, latency and coverage of the vehicle to Base Station (BS) link. The data recorded in the experimental measurements using live cellular signals are used to study the performance of two direction acquisition methods: the Angle of Arrival (AoA) estimation and downlink-based beam sweep. Next, the feasibility of signal tracking techniques exploiting the location of the vehicle and the BS are investigated to alleviate the need for continuous direction acquisition. The results show that the downlink-based beam sweep leads to higher Signal to Interference and Noise Ratio (SINR) than beamforming based on the estimated AoA. Evaluated tracking techniques are shown to be capable of correctly estimating the beamforming angle for distances in order of hundreds of meters when BS's location is known to the vehicle.**

I. Introduction

Data traffic patterns in vehicular applications differ widely from the ones generated by typical User Equipments (UEs) [1]. Direct communication between vehicles will be used for communication between proximate vehicles. In addition, cellular technologies can be used for delivering potentially high data rate sensor information and for enabling eventual information exchange among distant vehicles. In such cases, the existing cellular infrastructure will be used to deliver the information requiring the reliable, low latency, high bit rate uplink. As presented in [2], in cellular networks, the uplink coverage radius is generally much lower than its downlink counterpart due to limited transmit power of the device. Limited coverage (especially in the rural and suburban areas), together with large amount of connected vehicles constantly transmitting their sensor data, leads to uplink transmission being the potential bottleneck of the future vehicular communications.

Only few works target the uplink in the vehicular communications. In [3], the usage of Roadside Units (RSU) is discussed as a network element installed to gather data from connected vehicles. In this way, both coverage and congestion problems are solved by introducing additional signal transceivers to enhance network's capacity. However, the challenges still persist as it is hard to believe that RSUs will be globally deployed along all the roads. Beamforming algorithms exploiting millimeter wave frequencies [4] are a promising set of techniques to solve the high uplink throughput requirements imposed on the connected vehicles. However due to the large propagation losses, they might not be able to mitigate the potential coverage holes of the communication system.

The concept of using multi-antenna arrays is proposed in [5]. Authors note that installation of large antenna arrays, heavily constrained on the smaller vehicles, can be feasible on larger vehicles as trucks or buses. Although the main concept of the work in [5] is to improve downlink connectivity, it is easily extendable to the uplink communications. By using uplink beamforming, one can expect to improve the uplink throughput, reliability of the link or extend the coverage thanks to directional array gain.

These gains will only be achievable in the presence of a strong directional path towards the Base Station (BS) and with transmitter (vehicle) being aware of the direction towards which it should point the beam. In addition, a robust direction tracking procedure will be required to follow the imminent changes in the optimal beamforming angle, which can be challenging to achieve in the practical systems due to multipath propagation. Their applicability may become feasible in the rural and suburban areas with limited number of scatterers. In rich multipath urban scenarios, the potential uplink coverage/throughput bottleneck should be less harmful due to cell (and RSU) densification and therefore beamforming technologies may not be necessary.

In this work we present and experimentally evaluate the novel approach of using beamforming in the 1.8 GHz band for uplink vehicular communications in rural and suburban scenarios. We discuss the potential benefits and drawbacks of using different direction acquisition methods including beam sweeping and Angle of Arrival (AoA) estimation. Further we study two different methods for direction tracking exploiting measured live downlink Long Term Evolution (LTE) signal and Global Positioning System (GPS) information. The main aim is to assess the feasibility of practical implementation and benefits of beamforming, addressing the challenges related to finding the optimal beamformed direction.

The rest of the paper is structured as follows. Section II discusses the potential methods for selection of the uplink beam's direction. In Section III two tracking algorithms are proposed. This is followed by Section IV describing the conducted measurement campaign. The obtained results are shown in Section V-A and V-B for direction acquisition and tracking respectively. The work is concluded in Section VI.

II. Acquisition of beamforming direction

Uplink beamforming in sub-6 GHz frequency bands has not been widely utilized in cellular networks due to the device's hardware complexity and a limited gain with respect to other transmission modes [6]. The installation of multiple antennas would entail the need for additional transceiver chains impacting the price and energy consumption of the device. Additional space would be required to physically design antenna arrays with a desired spacing between elements. Even though vehicles are expected not to inherit these constraints applicable to the typical UEs, a major challenge persists. Vehicle would need to learn the optimal beamforming direction to focus the transmitted signal and benefit from high directional gains. Below, three possible ways of acquiring the beamforming direction are discussed.

Downlink-based AoA estimation

Assuming a cellular network operating in Time Division Duplex (TDD) mode, one can try to estimate the AoA of the received downlink signal based for example on Cell Specific Reference Signals (CRS) using estimation algorithms like Space Alternating Generalized Expectation-Maximization (SAGE) [7]. Then, by assuming channel reciprocity, the same direction would be used for uplink beamforming. This method can also be applied to the networks operating in the Frequency Division Duplex (FDD) mode with both uplink and downlink occupying similar frequency bands as for example LTE bands 3 or 7 [8]. The drawback of the AoA estimation lies in the computational complexity of the estimation algorithms. Also, in the case of FDD networks, the underlining assumption that the main downlink AoA is also the optimal uplink angle may not always be valid.

Downlink-based beam sweep

Another technique utilizing downlink cellular signals for finding the signal's direction is beam sweeping. In this method, a vehicle would use a subset of the possible beams to receive the downlink signals. Assuming the same TDD/FDD constraints as in the previous method, the beam resulting in, for example, the highest Reference Signals Received Power (RSRP) would be used for uplink transmission. Comparing with AoA estimation, beam sweeping should lead to more accurate beam selection, as potential non-idealities of the estimation process, especially in the estimation of weaker multipath components, are avoided. The complexity however still persists as sweeping through multiple beam options would be time consuming.

BS indicated precoding index

This technique is a mirror image of the methodology used for downlink beamforming in LTE [9]. A vehicle, would transmit its uplink data using a subset of beams. After BS estimates which of the beams would lead to the strongest received Signal to Interference and Noise Ratio (SINR), it would report its choice as a precoding index to the vehicle. This methodology does not set any specific condition even on the FDD bands and assuming slow vehicle's velocity, it should lead to the most accurate results. However, it would require standardization efforts and implementation in the BS therefore it is not included in the analysis conducted in this paper

III. Signal tracking techniques

Due to computational complexity (SAGE) or time required to perform the beam sweep, none of the discussed direction acquisition methods can be repeated with a high frequency. It is rather expected that the chosen direction acquisition method will be accompanied by a tracking algorithm used to estimate the imminent changes of the acquired direction over a short time before next direction acquisition procedure is performed. The valid question is therefore, for how long can the signal be tracked before there is a need for another direction estimation using one of the aforementioned methods? This distance would depend on the environment and is expected to be much longer in the rural and suburban areas rather than dense urban ones where frequent changes of direction are expected due to the multipath propagation. As a part of this work, we experimentally evaluate the length of the tracking distance based on the conducted measurement campaign utilizing live cellular signals. Two different signal tracking techniques are studied depending on information available at the vehicle.

Beam tracking with no GPS information

This simple tracking method, as presented on Figure 1, assumes that GPS coordinates of the serving cell are not known to the vehicle. At the beginning there is a so-called *warm up* phase. In two positions, separated by a driven distance d, the real direction is acquired using one of the methods presented in Section II. Then the change in the beam direction $\Delta\beta$ is computed as the difference between beamformed directions in these two positions. Since the GPS coordinates of the BS are not known, it is assumed that the same change trend will continue and the angle should be adjusted linearly based on the driven distance, as for example after distance $2d$ is driven, the beamformed angle should be adjusted by $2\Delta\beta$. This simple tracking method has some limitations. Only if the distance to the BS is sufficiently long one can assume the angular change of the beam direction will persist. Otherwise, for the same driven distance the angle change would be much lower than $\Delta\beta$ if after the warm up phase the vehicle would start to recede from the BS leading to incorrect estimation of the angle.

Beam tracking with GPS information available

By exploiting the GPS information of the BS, the impact of the distance to the BS can be removed. In this method, as presented on Figure 2, in each position the direct path towards the BS can be computed based on the GPS coordinates. After initial direction acquisition in the first point, the predicted beamformed angle after distance d is estimated based on the change in the angle of the direct path $\Delta\gamma$. In this method, the angle change $\Delta\gamma$ can be constantly adjusted as the difference between angles of the direct paths in the last two positions removing the impact of the distance to the BS.

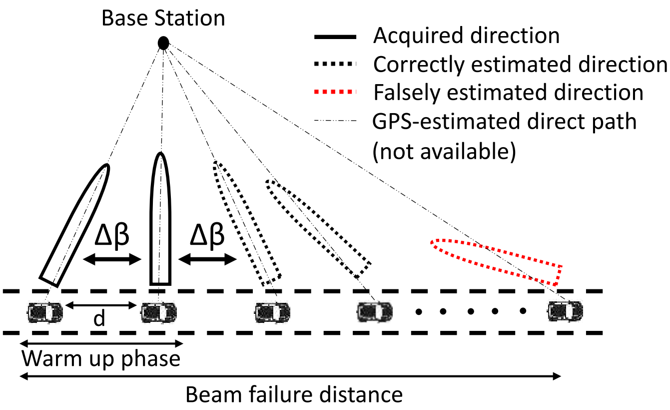

Fig. 1. Beam tracking exploiting only acquired signal direction

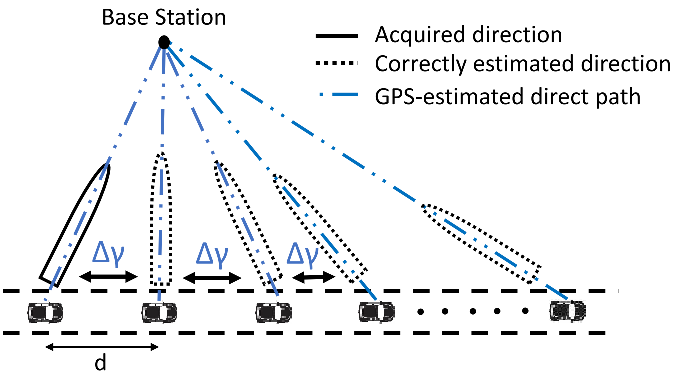

Fig. 2. Beam tracking exploiting GPS coordinates of the serving cell

IV. Measurement Campaign and Post-Processing

Given the practical difficulties of obtaining uplink measurements in real cellular networks, the methodology used in this study is based on a measurement campaign where live cellular signals are recorded in the downlink by using a multi-antenna software defined radio setup. The raw measured signals are processed offline, and different direction acquisition methods and signal tracking techniques are studied. Our analysis is based on the assumption that the main signal direction estimated in the downlink can be used for uplink transmission. This holds in case of TDD or FDD modes with sufficiently close operational bands, as highlighted in Section II. The downlink SINR is used to compare the direction acquisition techniques, by pointing the beams towards the acquired direction to receive the signal; while downlink-estimated AoA is used to assess the performance of tracking techniques.

The measurement campaign was performed in Aalborg in northern Denmark. In the measurement campaign, the downlink LTE signal from two Danish mobile operators operating in 1.8 GHz band was recorded using a multi-antenna measurement setup based on the Universal Software Radio Peripheral (USRP) boards thoroughly described in [10]. USRPs provided a set of fully digital receiver chains for a sixteen antennas circular array that was used to record the raw I&Q samples of the LTE signal for the offline post-processing. Every five seconds, a snapshot containing 100 ms of LTE signal was recorded. In total four different routes were driven across suburban, rural and highway scenarios spanning more than 150 km distance [5]. One example of such route is presented on Figure 3, together with the vehicle used to conduct the measurements.

Fig. 3. The example of the driven route in a suburban environment and the measurement vehicle

Post-processing for direction acquisition

After the measurement campaign, in the offline post-processing the direction acquisition methods are studied. For each snapshot recorded in the measurement campaign, after synchronization to the network and channel estimation, the AoA of the incoming signal is estimated using SAGE [11]. After centering the receiver beam at the estimated angle, the SINR of LTE System Information Block 1 (SIB1) control channel is computed. On the other hand, to study the downlink-based beam sweep, the data from each snapshot is independently beamformed using 360 different beams pointed in different directions in azimuth domain. The beam with the highest reported RSRP is used for further decoding of the SIB1 control channel and SINR computation. Finally, since together with the LTE signal, the GPS coordinates of the vehicle were saved, knowing the GPS coordinates of the BS, the angle of the GPS-based direct path towards the serving cell is estimated. The SIB1 SINR is again computed after centering the beam towards the found angle. The same beam shape with Half Power Beamwidth (HPBW) of 22.5° is used for both methods.

Post-processing for signal tracking techniques

Figure 4 presents the AoA estimated with SAGE together with the computed GPS-estimated direct path towards the BS for a driven fragment of the road, after removing the impact of the vehicle's heading direction. As can be noticed, there are

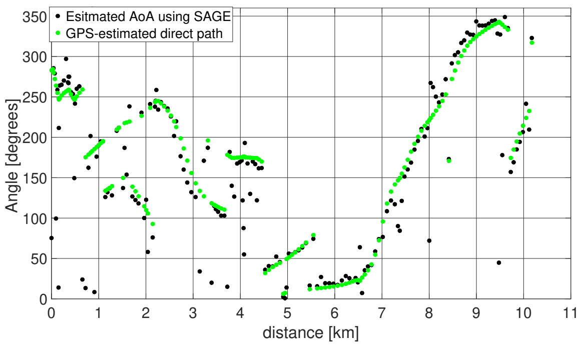

Fig. 4. The estimated AoA compared with GPS-based found shortest angle to the BS

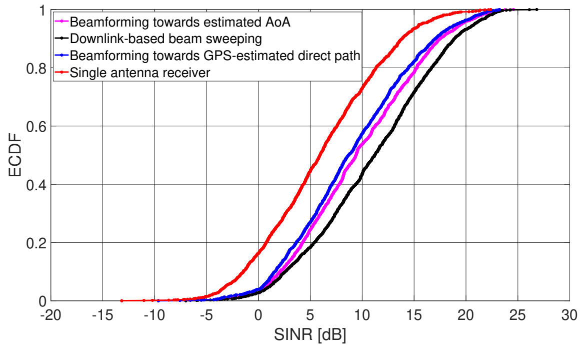

Fig. 5. Comparison of downlink performance of direction acquisition techniques in suburban and rural scenarios

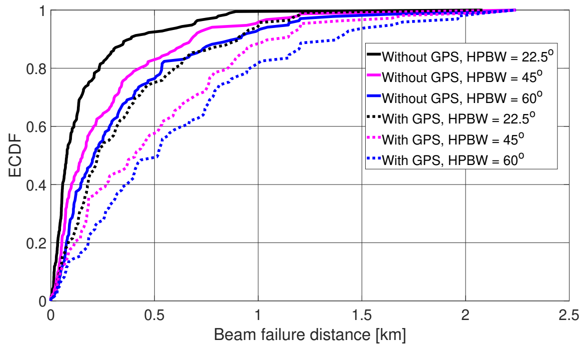

Fig. 6. Maximum tracking distance in suburban and rural scenarios

multiple fragments where estimated angle gradually changes with the driven distance and signal tracking seems feasible. As measurements were conducted over large distances, for each driven road there are multiple positions when serving cell changed. This can be noticed on the figure with abrupt changes of the GPS-based geometrical direct path. The first step is to split the recorded data into chunks of continuous snapshots connected the same serving cell. In order to facilitate the studies on tracking techniques, only the chunks of the road containing minimum ten continuous snapshots were used. Please note that due to varied speed of the vehicle, the distance between snapshots is not uniform distributed.

To study the quality of beam tracking algorithms, the metric called *beam failure distance* is defined and shown on Figure 1. For each snapshot, the difference between the estimated angle using tracking techniques and the real AoA found based on the direction acquisition of the strongest path estimated using SAGE is computed as a *tracking error*. Assuming the vehicle will center the uplink beam towards the estimated angle, we check if the tracking error is lower than the half of the HPBW. In such a case even though the uplink beam is not precisely centered, more than half of the transmitted energy will propagate towards estimated AoA. In case the tracking error is higher than HPBW, it is assumed that beam tracking failed and the beam failure distance has been reached. In this situation direction acquisition as explained in the previous section is required. Please note, that our definition of the beam failure distance is less strict that the beam coherence time defined in [12], as we do not rely on the alignment with the BS's beam but only on its physical location.

V. Performance analysis

A. Acquisition of beamforming direction

Figure 5 presents the Empirical Cumulative Distribution Function (ECDF) of the computed downlink SINR for the signals beamformed towards the acquired directions using the AoA estimation and downlink-based beam sweeping. Additionally, the performance of blind beamforming towards the GPS-estimated direct path and single antenna receiver are added as a reference to compare the loss with respect to the AoA estimation. Due to the reasons explained in Section II, downlink-based beam sweep provides up to 1.6 dB median SINR gain over an AoA-based beamforming and 5 dB gain over a single antenna system. Quite surprisingly, centering the beam towards the estimated AoA provides only a slight gain versus centering the beam on the GPS-estimated direct path. This can be explained, as in more than 70% of the snapshots estimated AoA was approximately the same as the direct path. Please note that measurements were taken in the rural and suburban areas where the likelihood of main AoA coinciding with the direct path is higher than in the dense urban scenarios.

Although, one should not expect that the presented downlink SINR would fully reflect the observed uplink SINR at the BS due to the presence of multiple users and different interference patterns, the presented trends should persist in the rural and suburban areas where interference is limited. Based on the obtained results, it is clear that the downlink-based beam sweep is more reliable method for direction acquisition than AoA estimation. Moreover, if sweeping operation is not possible, centering the beam towards the GPS-estimated direct path to the BS should be considered in place of AoA estimation due to reduced computational cost and similar performance.

B. Signal tracking techniques

Figure 6 compares the performance of studied signal tracking techniques for different widths of the beam. The ECDF of

TABLE I

PERIODICITY OF DIRECTION ACQUISITION METHODS BASED ON THE COMPUTED TRACKING DISTANCE FOR VARIOUS SPEEDS

Periodicity of direction acquisition						
	With GPS information			**No GPS information**		
Speed/HPBW	60°	45°	22.5°	60°	45°	22.5°
30 km/h	62 s	49 s	27 s	24 s	18 s	9 s
50 km/h	37 s	29 s	16 s	14 s	11 s	5 s
80 km/h	23 s	18 s	10 s	9 s	7 s	3 s
100 km/h	19 s	14 s	8 s	7 s	5 s	2.5 s

the beam failure distance - the distance when tracking error became larger than the HPBW are presented. As expected, for both techniques, the wider the beam, the longer the tracking distance, as better is the tolerance for the small tracking errors. This results in a trade-off between directional gain of the array and the tolerance for the direction mismatch. Using the narrowest beam (22.5°) and exploiting the GPS coordinates of the BS, in 50% of the cases the tracking distance is longer than 220 m. With the wider beams, median tracking distance can stretch out to 400 m for 45° HPBW or 500 m if HPBW is 60°. Table I presents the required periodicity of triggering direction acquisition methods for different vehicle speeds computed based on the median beam failure distance.

As can be noticed, there is a significant improvement if the GPS coordinates of the BS are used for the tracking. This can be explained, as in most parts of the driven roads, the distance to the BS was not constant and varied from positions very close to the BS where angle change was large even for small driven distances, up to positions located far away from the serving cell, where this change was negligible. The knowledge of BS's location and therefore the distance helps to improve the tracking performance such that the expected periodicity of direction acquisition procedure can be extended. In all cases the median tracking distance is in a range of seconds, allowing the time consuming direction acquisition techniques to be performed less frequently or more accurately by, for example, allowing more iterations of SAGE algorithm or more precise beam scan. The upper-bound limits of the tracking performance are constrained by the coverage of the serving cell and the amount of continuous snapshots being recorded.

Focusing on the low tail presented at the Figure 6, in more than 20% of the cases the tracking distance is shorter than 200 m. This situation can partially be justified, due to the assumed methodology. The tracking error is computed as a difference between estimated angle and computed AoA. For some parts of the road, due to the multipath propagation, the real AoA of one of the first estimated snapshots (after the warm up phase) was computed from the unexpected direction (as can also be seen at the beginning of Figure 4), leading to instant beam tracking failure. It is expected, that by extending the warm up phase to more than two snapshots or by reducing the distance d between direction estimations the tracking performance would be improved.

VI. CONCLUSIONS

In this paper the concept of uplink beamforming for vehicular communications using sub-6 GHz bands is analyzed. Different methods of direction acquisition and techniques for signal tracking are discussed. Presented concepts are experimentally evaluated based on live LTE signals recorded during extensive measurement campaigns. The results show that beamforming towards the direction found using the downlink-based beam sweep should lead to improved performance over an AoA estimation. In rural and suburban scenarios, the acquired direction was found to be tractable over large distances in the range of hundreds of meters, extending the required direction acquisition periodicity to tenths of seconds. The availability of GPS coordinates of the serving cell can further improve the tracking performance and lead to more than a 100% improvement of tracking distance versus schemes which do not use information on the GPS coordinates of the BS. Results presented in this paper show that the sub-6 GHz uplink beamforming can be a feasible technology to enhance uplink coverage for the vehicular communication.

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