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Reflecting Surfaces for Beyond Line–Of–Sight Coverage in Millimeter Wave Vehicular Networks

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***Abstract*—Millimeter Wave (mmWave) mobile communication networks are envisioned to provide high performance radio links as required by emerging vehicular applications such as remote driving and massive automotive sensing. However, the high penetration loss and thus a high blockage probability embody the greatest challenges in farming this frequency spectrum. For this reason, the specific utilization of reflecting surfaces, especially so–called reconfigurable intelligent surfaces (RIS) introduce a controlled and focused reflection towards the designated receiver, if the line–of–sight is obstructed. In this work, we present a latest extension to our vehicular mobility and mobile network simulation environment, which allows for coverage analysis, network planning and the evaluation of context–aware beam management strategies. Preliminary results prove, that even in a weak coverage scenario with one base station, the deployment of properly disposed RISs leads to the achievement of predefined coverage goals even with imperfect context information. Based on the outcomes, new rules to ease the placement of RISs for network planning tasks might be derived in future.**

I. Introduction

The enormous data rate requirements of future connected and autonomous driving as well as of massive automotive sensing [1] have led to the exploration of the millimeter wave (mmWave) spectrum for vehicular communications. Although in this frequency range a high coherent bandwidth in the range of one gigahertz is available, the radio channel conditions are substantially different to the frequency spectrum traditionally used for mobile networks. Directional communication by means of beamforming needs to be leveraged to overcome higher path losses, but the necessity of beam alignment complicates the traditional radio access procedures.

One of the major challenges is the high obstacle–related penetration loss. For this reason, non–line–of–sight (NLOS) conditions are only conceivable when utilizing reflecting surfaces. However, the exhaustive exploration of reflections is time consuming and volatile. With reconfigurable intelligent surfaces (RISs), the general idea of leveraging signal reflections for beyond line–of–sight communications is even escalated. Common surfaces tend to reflect signals e.g. according to the law of reflection. Contrarily, the angle of the reflected electromagnetic wave is dynamically adjustable independently of the incident wave's angle when using a RIS (Figure 1). This ability of influencing the propagation channel is expected to become a game changer for mobile communications especially at the mmWave domain. As a consequence, future network planning is expected to extensively utilize the capabilities of RISs for interference avoidance and coverage optimization.

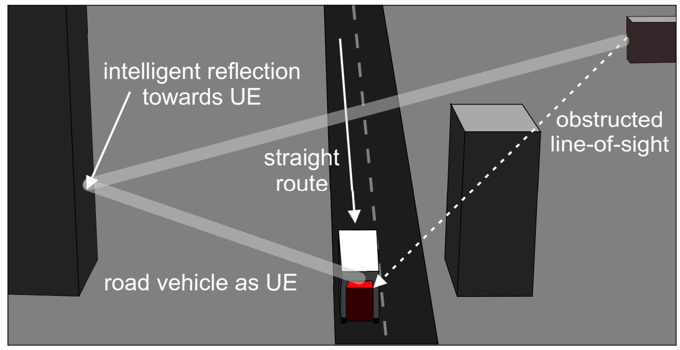

Fig. 1. Potential of considering reflecting surfaces for enhanced beyond line–of–sight coverage of 5G mmWave mobile networks. A RIS can be configured to reflect radio signals towards some target UE to overcome an obstruction.

In this paper, we present our integrated simulation framework for exploring the potentials of applying RIS for coverage optimization in vehicular networks. Within the lightweight ICT–centric mobility simulation (LIMoSim)–based [2] simulation environment, RIS elements can be placed at the playground, while the mmWave network simulation is based on the network simulator 3 (ns–3) mmWave module from [3]. Based on this approach, a comparative coverage analysis is performed to reveal the benefits of the deployment of RISs and thus the specific utilization of steerable reflection paths. Additionally, first insights are discussed to facilitate the network planning tasks by deducing rules for RIS placement strategies.

The remainder of the paper is organized as follows: In Section II, related work and its effect on this paper is discussed. The overall concept is presented in Section III. Subsequently, a sample vehicular application use case is introduced and evaluated in Section IV, before Section V concludes this work.

II. Related Work

In mmWave mobile networks, it is believed that radio signal propagation needs to be focused by beamforming to strive against the severe path loss. Fundamentals on beamforming as well as considerations on the disposable link budget at the mmWave domain can be found in [4]. The resulting directional transmission constitutes challenges regarding common radio network signaling like e.g. cell discovery and the initial access procedure, since a proper beam alignment needs to be determined. In [5], authors present different approaches for addressing these challenges such as context–aware acceleration of cell attachment by taking information of the environment into account.

With a negligible penetration of obstructions, the utilization of reflections is crucial for mmWave mobile networks beyond line–of–sight (LOS) conditions. A study on the reflectivity of common building surfaces is given by [6]. The coverage enhancement due to passive reflectors is surveyed by means of channel sounding in [7].

In smart radio environments, metasurfaces influence the wireless communication channel in a controlled fashion. Hereby, RISs are able to support signal propagation towards the destination by electronically adjusting their angle of reflection. A comprehensive introduction to this topic can be found in [8]. While the utilization of relays for beyond LOS vehicular communication e.g. in cities is discussed in [9], authors in [10] particularly stress the potential of RISs in terms of energy efficiency and implementation complexity compared to relays.

In [11]–[13], authors model the controllable reflection characteristic of RISs and finally the path loss of an RIS–enabled channel. In this work, the path loss model according to eq. 18 of [13] is used which is only applicable within the there defined far–field distance. Since this model only represents a reflected path, the propagation loss implementation of [14] is still used for the LOS propagation paths and applies this reflection model, if the LOS is obstructed. As a basis, LIMoSim determines whether there is a LOS to a base station or a RIS by modelling obstructing buildings and vehicles as objects with a defined mobility behavior. This information is also shared with ns–3, where further modular channel models may be taken into account. With the focus on the sketched propagation loss model in this work, for the ns–3 mmWave module [3] the default parameters are retained. More details on the interplay of LIMoSim and ns–3 can be found in [2].

III. Coverage Enhancement of 5G mmWave Networks by means of RIS

Since the penetration of obstacles is not viable for mmWave radio links, the LOS coverage of mmWave cells is believed to be rather poor. However, as pointed out in [7], signal reflections on walls might be leveraged for enhancing the network coverage. With RIS, these reflections become controllable, so that the angle of reflection can be purposefully steered towards the targeted receiver.

This basic concept is analyzed in a straightforward validation scenario as depicted in Figure 1. Within the blockage area, the building on the left–hand side of the road serves as reflection surface. The obstructed track section is reachable according to the well–known law of reflection. Additionally, when deploying a RIS, the angle of reflection is configurable, i.e. a single RIS on the building surface may support the coverage of the complete obscured area via a controlled first–order reflection tracking the vehicle passing by.

According to the aforementioned model of [13], the vehicle's experiential path loss along its straight route is depicted in Figure 2 for different RIS dimensions. While *large* dimensions lead to a high reflection gain and thus low path loss, the reflected beam is quite narrow, so that a beam alignment task becomes more challenging. The RIS–size can even be *fitted*

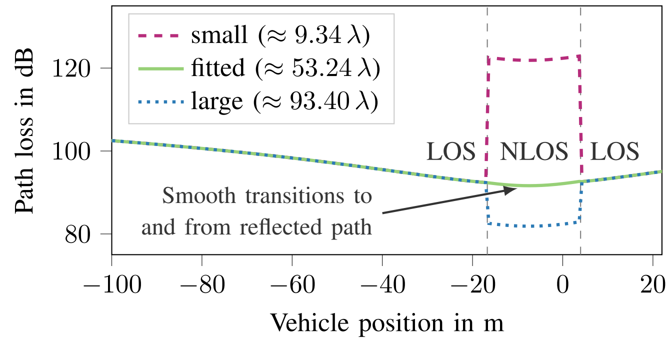

Fig. 2. Impact of RIS size on path loss. The size is given as the edge length of a square shape. The larger the RIS, the lower the path loss. A smart choice of the RIS's dimensions could lead to a seamless transition between LOS and NLOS conditions (*fitted* curve).

to the LOS path loss to allow for a smooth transition in the vehicles receive power while switching between LOS and the reflected path. Although this is strongly dependent on the LOS and NLOS distances, future RIS implementations may even be capable of dynamically using a subset of their surface for signal reflection to allow for a flexible balance between the reflection gain and beam width.

On the one hand, the RIS elements need to be small to satisfy the far–field constraint of the used model. On the other hand, with respect to the overall mobility simulation, the maximum necessary RIS dimension (and thus reflection gain) can be figured out for a given scenario to meet the link budget and the coverage goals.

IV. Case Study: Campus Shuttle Bus

As exemplary application use case, the network coverage along the track of a notional self–driving shuttle bus at the north campus of the TU Dortmund University is analyzed. The map data including buildings and roads are extracted from OpenStreetMap.

A. Coverage goal

The entire route is to be covered by a single mmWave base station supported by RISs. It consists of the two central rectangular tracks shown in Figure 3, disregarding the approach roads. Finally, this setup shall elaborate on the general advantage of RIS deployment for mmWave networks based on an application–oriented analysis.

As discussed in Section II, the RISs are modeled according to [13]. The angle of reflection is limited to $\theta_{\text{max}} = 80°$ from the surface normal and the dimension of the RISs is dynamically reduced if the vehicle is close, in order to always meet the far–field constraint for the application of the model. Their maximum dimensions are limited to edge lengths of 0.5 m, i.e. 46.70 λ at 28 GHz. The cutoff of a subset of the RIS size leads to a wider beam width and a reduced reflection gain. Further peculiarities regarding the implementation of RISs and their control via non–ideal communication channels are not taken into account at this stage and remain open for future work. However, after a fundamental analysis of the base station and RIS placement in terms of road coverage, the simulation

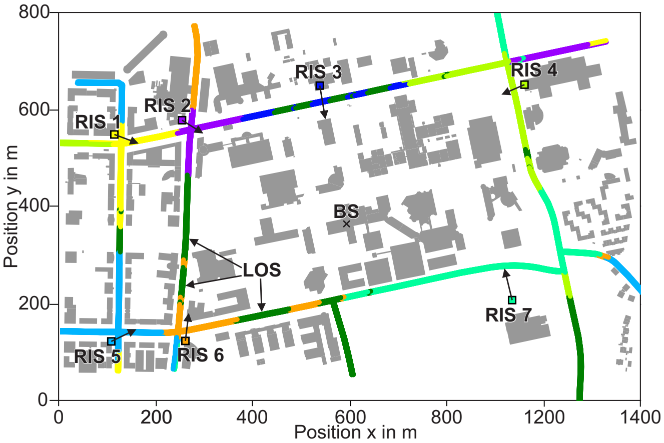

Fig. 3. Coverage evaluation for LOS and RIS–enabled reflected paths at an exemplary deployment scenario at the north campus of TU Dortmund University. The road coverage is marked in dark green if there is a LOS and otherwise in the respective RIS color. The center, rectangular track is the route of a fictive shuttle bus use case. (Map data: © Open–StreetMap Contributors, CC BY–SA)

of inaccurate vehicle positions allows for the examination of the effect on misaligned reflected beams.

In summary, the coverage analysis is thus divided into three steps: First, only the LOS paths from a central base station are considered. In addition to that, the coverage enhancement due to the deployment of RISs is assessed. Finally, imprecise vehicle positions are simulated to account for the misalignment of the RIS reflected paths to the vehicle.

B. RIS placement

Figure 3 illustrates the coverage regions within the campus scenario. In doing so, LOS paths to the base station are always preferred. The RISs are placed arbitrarily to reach obstructed, i.e. NLOS regions while having a line–of–sight to the base station itself. While sophisticated network planning and deployment optimization techniques might be considered for an automated, heuristical placement in future, fundamental recommendations and rules are being derived from this preliminary approach to facilitate further efforts.

In a first step, NLOS areas are determined, which need to be served by RIS–enabled reflections. Second, suitable buildings are selected to place RISs for covering those areas. RISs on top of buildings close to crossroads areas are preferable to serve more than one road section by a single inserted RIS. After the choice of positions, the surface normals are initially oriented towards the base station, since this leads to a lower path loss according to the RIS model. If some of the blockages are still present, the RIS orientation and position are slightly adjusted. At the end, the base station and the inserted RISs ought to cover the targeted road sections, which will be analyzed in more detail in subsection IV-D, especially in terms of a potentially imprecise configuration of the RIS reflected path.

In general, contiguous regions like covered by RIS 7 might be of advantage, since a smooth beam tracking may take place and only needs to concentrate on the current angular area for a particular mobile device. In contrast to that, the interrupted road section coverage in front of RIS 3 might lead to a back and forth switching between LOS and reflected path. This either requires a more comprehensive assessment of possible beam directions or more sophisticated beam switching strategies like staying at a RIS–enabled path in anticipation of a recurrent LOS blockage instead of temporary returning to the LOS path and shortly recovering the reflected path.

C. Beam management

For each simulated vehicle position on the road, the dominant path and the related path loss are computed in LIMoSim. The LOS path is always preferred, while the reflected path with lowest loss is selected in NLOS conditions. In real world applications, the exploration of the dominant path by an exhaustive beam search might be time consuming and inefficient. However, context information could be gathered as database to associate beam pointing directions with vehicle positions [15]. Based on that, the vehicle's position suffice to determine the beam and reflection configurations and apply it on the base station and the appropriate RIS, respectively.

Different from the base station and RIS sites, the end devices are believed to have rather strong size restrictions and efficiency constraints. Due to that, the effort for the beam alignment of the UE might be kept modest by using high beam widths by means of low dimension phased array antennas and virtually omnidirectional antenna elements, for example. For this reason, the beam alignment of the vehicle is provisional considered negligible and out of scope of this study.

The vehicle's position might be available to the network as part of vehicle–to–everything (V2X) communications or can be approximated from the mobile radio network itself, e.g. like discussed in our previous work [16]. Additionally, beam tracking procedures and beam refinement operations might cause a successively more accurate alignment in case of initial imperfect position information. This means, a coarse path selection is done based on a position information to accelerate the alignment for the initial access and after a path switch–over. Subsequently, the beam alignment might be refined by self–contained signal measurements and a beam tracking algorithm like presented in [17].

D. Results and Performance Evaluation

The conducted simulations concentrate on the initial beam alignment based on imprecise feedback of the vehicle position. For this, the position information is distorted by a three–dimensional, zero–mean normal distribution with standard deviations of 1 m to 6 m in each dimension to account for a reasonable imprecision of localization techniques. Based on that, the reflected beam points to a deviating direction, which leads to a reduced reflection gain.

As previously mentioned, the coverage goal consists in the central, double rectangular area of Figure 3, leaving out the approach roads at the edges of the displayed map. In Figure 4, the empirical cumulative distribution function (ECDF) is illustrated as a statistical coverage analysis for these targeted road sections. The route is sampled with 8221 positions and the simulation is conducted 20 times for each analysis. While

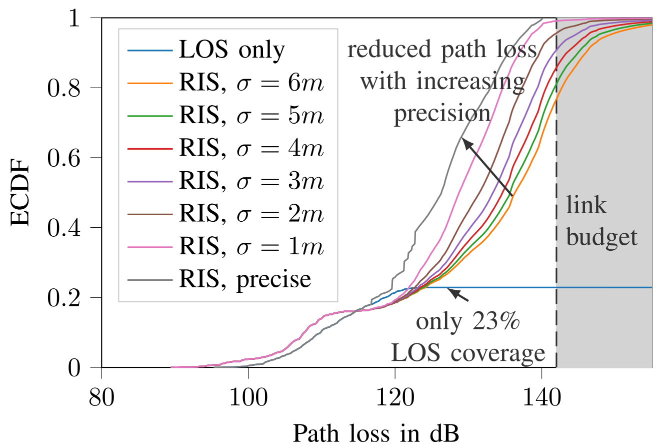

Fig. 4. Comparison of the path loss distribution. Only considering LOS, a poor coverage of 23 % is reached, whereas an elaborate RIS placement enhances the overall coverage. Even with distorted vehicle position information and thus misaligned reflected beams, the path loss remains within the link budget for 91 % of the track for $\sigma = 3\,\mathrm{m}$.

the LOS–only coverage has a quite low path loss, most of the region is out of range leading to only 22.86 % coverage in total. On the contrary, the RIS deployment leads to a comprehensive coverage with mostly better signal strength.

In addition to that, the RIS–enabled mobile network provision is maintained even with more distorted feedback of the vehicle position, i.e. the vehicle position superimposed by a normal distribution with an increased standard deviation σ. As expected, the higher σ, the more likely a higher path loss. However, although the path loss distribution is impaired, the route can be serviced mostly within the link budget of 142 dB as proposed in [4] for outdoor scenarios at 28 GHz. In the aggregate, the RIS deployment allows for network coverage on 100 % and 91 % of the predefined campus shuttle route in the undistorted/precise case and with $\sigma = 3\,\mathrm{m}$, respectively.

V. Conclusion

Upcoming mmWave mobile radio networks escalate the achievable network capacity. At the same time, the beam management and obtaining adequate coverage are challenging tasks. To support mobile network subscribers like vehicles, a reliable solution to overcome LOS blockage is required. For this, relying on random multipath occasions like signal reflections on building walls might not suffice.

The cutting–edge RIS technology enables a purposeful intrusion into the radio environment by purposefully directing reflected signals towards the targeted receiver. Within our joint mobility and network simulation framework, the anticipated advantages and challenges of RIS deployment to enrich mmWave networks have been illustrated. Preliminary results prove the coverage enhancement capabilities for an exemplary vehicular application use case. In case of a dynamically adjustment of the utilized RIS surface size, a flexible balance between a high reflection gain and robustness against beam misalignment can be achieved.

In future work, context–aware and machine learning–based beam management procedures will be incorporated and further, aerial vehicular applications will be analyzed.

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