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Abstract: *Ray-based and hybrid propagation models are today considered as valuable solutions to fulfill 5G wireless channel modeling requirements. They are a complement or alternative to the stochastic approaches when link-level and system-level simulations deal with millimeter-wave (mmWave), ultra-dense deployment and/or large antenna arrays. The present article proposes an extension of an urban ray-based model for the assessment of a 60-GHz outdoor small-cell network. The multi-paths are predicted from interactions with the static environment, but also with randomly-positioned vehicles and user-bodies. Both the vehicles and the user-body generate ray-path blockage, and (in case of the vehicle) new propagation paths. This sometimes affects the cell selection or beam orientation, and significantly changes the received signal strength and inter-cell interference. In this paper, the blockage effect is first modelled and assessed in simple scenarios before it is introduced into a whole mmWave small-cell network simulation via a stochastic process. The impacts on the signal strength, interference level and the signal-to-interference ratio are evaluated and discussed.*

1. Introduction

Most PHY-layer techniques designed for 3G and 4G systems have been evaluated and refined through link-level or even multi-link simulations, using stochastic propagation channel models, from the simple tapped delay line models to the MIMO-compliant geometry-based bidirectional models like the ones proposed by the European COST 273 action [1] or the WINNER projects [2][3]. Today however, there is a growing interest for the introduction of deterministic or hybrid solutions, which typically rely on ray-tracing or ray-launching, at early research and final validation stages. There are a few reasons for this. The extension of the stochastic channel models to fulfill 5G requirements is a challenge. The fact that channel properties strongly differ between the well-known sub-6GHz frequencies and the millimeter-wave (mmWave) spectrum is one difficulty. The need for accurate spatial consistency and 3D directions in ultra-dense network simulations are two other ones. New channel measurements are required; research activity is intensive today, but such measurements and subsequent model derivation necessarily take time. In addition, higher models complexity is expected. The recent METIS channel model [4] proposes a map-based approach as an alternative to stochastic models which may not be applicable in all cases. Such models can generate all large-scale and small-scale channel properties or may be used to feed a stochastic modeling with some deterministic large-scale parameters. Beside, the MiWEBA European project has recently released a channel model with hybridation of deterministic reflected paths and stochastic components [5].

The present article exploits the ray-based model described in [6] and adjusted to 60 GHz [7] to assess the performance of an outdoor mmWave small-cell network. Stochastic components are integrated to reproduce the high sensitivity of the multi-link propagation scenario to non-static objects, i.e. the body of the user itself and large vehicles (e.g. buses, trucks or vans) driving in the streets. The blockage of the 60-GHz wave by the human body or large vehicles strongly impacts the link quality and dominant propagation directions, leading to changes in the cell selection, beam selection, interference levels and even the connectivity rate. The motivation for the use of hybrid solutions using near field self-obstruction user-body modelling in mmWave channels is given in section 2. The system-level simulations reported in section 3 have two objectives: first, evaluate the interest of the mixed approach compared to purely static predictions; second, assess the performance of a mmWave outdoor small-cell network from consistent channel simulations.

Conclusions and recommendations are given in section 4.

2. MmWave channel modelling

At mmWave frequencies, due to the small wavelength, the electrical size of most in-street objects becomes significant. Channel models considering buildings and vegetation [7] can be predicted using purely deterministic approaches, using ray-tracing or ray-launching tools as the positions of these objects are fixed. However, to model in-street objects which are more dynamic in nature (not fixed) like vehicles and humans some stochastic components are required. In this work, a hybrid model is proposed where the obstruction by large vehicles and the self-obstruction caused by user body are stochastically introduced.

a. Large vehicle obstruction

Most in-street objects like vehicles, pedestrians, lampposts, urban furniture etc. can obstruct the dominant path at mmWave frequencies. The impact of the obstructions may sometimes not be visible due to multipath and based on the relative positions of the transmitter and receiver. A scenario in which obstruction by a large vehicle (for e.g. bus) in the street; of a user located in close vicinity of the object is shown in Fig. 1. Here the different propagation paths impacted by the large vehicle obstruction are shown. The impact of the obstruction caused by a large vehicle at various positions with reference to a fixed user is illustrated through simulations, shown in Fig. 4. The large vehicle obstruction and the user-body self-obstruction are both considered in the simulations of the whole network discussed in section 3b.

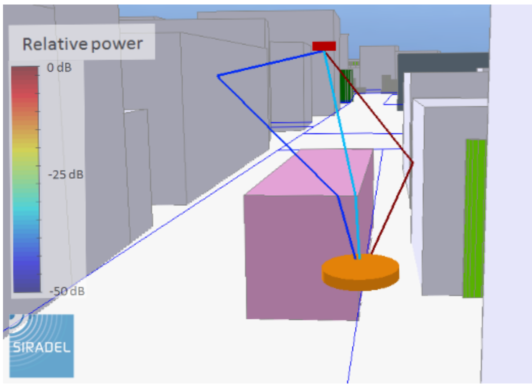

Fig. 1. Illustration of propagation paths with bus obstruction.

b. User-body model

The near-field self-obstruction caused by the user body itself is also of great interest as this kind of obstruction is omnipresent. Various diffraction models have been used in literature [4][8][11]. The Knife Edge Diffraction (KED) models have been widely used to calculate the loss due to human body obstruction [4][8]. And the double knife-edge model (DKED) is found very representative of the reality. It has been proposed in the METIS model [4] to consider the human body as an infinitely long screen with two edges.

However, the knife edge model underestimates the shadowing when the antenna is close to the obstructing body. A more appropriate approach is to consider the human body as a cylinder with uniform dielectric properties. At 60 GHz frequency, the electrical size of the human body is relatively large and the body must be considered as a rounded obstacle instead of a sharp edge. Then the Uniform Theory of Diffraction (UTD) for rounded objects or the rounded edge model by ITU-526 [10] can apply. In particular, the UTD-based creeping wave model was shown to perform well as compared to the exact solution [11], and is proposed for on-body channel predictions.

For implementation simplicity, we have chosen the [10] formulation for our model. An extra attenuation due to a curved obstacle is added to the KED loss. The relevance of this model is well-known for large range propagation, but we decided to evaluate its accuracy for the short-range obstruction that is considered here. It is compared to the creeping wave model results published in [11]. In this article, the human body is modelled as a cylinder of radius r=0.2m. Omni-directional antenna is considered for the receiver which is at a distance d=0.205m from the centre of the cylinder. The receiver is oriented at different angles ϕ as shown in Fig. 2a. Frequency is 60 GHz. The obstruction loss from the single knife-edge, creeping wave, and the ITU-526 rounded edge models are plotted together in Fig. 2b, showing good agreement between the two latter ones, and strong underestimation from the first one. Note the creeping wave model predictions on this scenario have been validated against measurements [11].

In the proposed implementation here, the body orientation is random and the distance between the body centre and the antenna is d=0.4m. In this situation, and if we assume the base station is far away from the user, the shadow region is 60° wide, thus covering 16.7% of the plane.

We decided to consider only one diffracted edge instead of two. The loss in the shadowed area where both diffracted paths are of same order is very strong and the improved accuracy offered by the double-edge approach will not have any impact on the simulations. The red plot in Fig. 2b illustrates the loss that is computed in the remaining of our study, i.e. with d=0.4m.

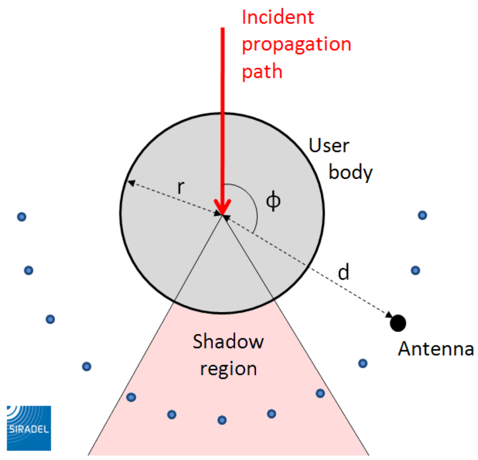

Fig. 2a. User-body self-obstruction.

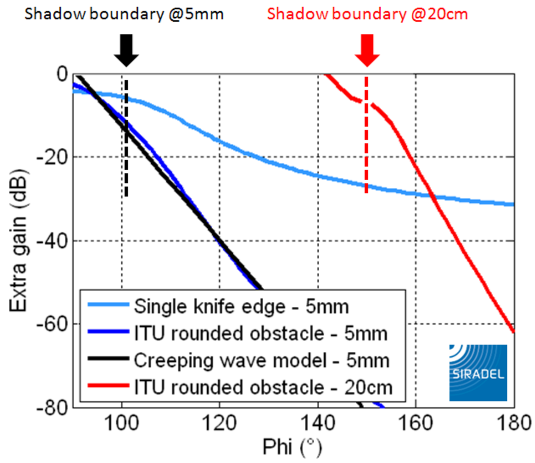

Fig. 2b. Obstruction loss from user body.

3. Dense small-cell network simulations

Based on the obstruction models presented in section 2, ray-based simulations have been performed on the following dense small-cell network. The designed network from [7] is expected to provide seamless outdoor coverage using deterministic tools without considering in-street obstacles like user-bodies or vehicles, which are introduced in the scenario in the following sections.

a. General simulation framework & Scenarios

The network is composed of 18 small-cells operating at 60 GHz, deployed over a 0.090 km² wide area. The average inter-site distance (ISD) is 78 m, while the maximum ISD is 110 m. Each small-cell has only one sector.

The small-cells are assumed to be installed on lampposts at height 7m above the ground. They are equipped with an automatically steerable antenna. The half-power beamwidth (HPBW) is 22° with maximum gain 18.5 dBi. The radiation pattern is assumed to be perfectly shaped, i.e. without any significant side-lobe. The transmit power is adjusted such the EIRP is 40 dBm as allowed in current FCC rules.

Fig. 3. Small-cells deployment (red dots) in 300 m x 300 m area.

The performance statistics are obtained from a Monte-Carlo process, where users are dropped randomly along the sidewalks with finite throughput demand. Multi-path propagation, cell selection, beam selection and interference calculations are executed at each iteration, as explained with more details in [7]. The IEEE 802.11ad link performance is considered [9].

An orientation is randomly set to each user, and the user-body obstruction affects the multi-path propagation data based on the model described in section 2. Large vehicles are randomly dropped in the streets, as shown in Fig. 3 by purple rectangles. The number of vehicles has been arbitrarily fixed: 170/km². Their length is 12 m. They completely block any incident propagation path, but they also produce new reflections and diffractions. Metallic material is considered.

b. Small-cell simulation results

The small-cell simulations have been performed by considering at first only a single street containing two small-cells for preliminary analysis separately on the large vehicle and user-body obstructions. Then simulations are performed on the whole network considering both the stochastically based obstructions together.

i. Two small-cells simulations

A street containing two small-cells separated by 80m is considered here. The purpose is to assess the impact of obstruction caused by large vehicles or the user-body on inter-cell interference and user performance. Note that there is no outage in absence of large vehicles or user-body obstruction.

The effect of bus obstruction (large vehicle) on a fixed user located at the blue star shown in Fig. 3 is simulated. This represents a scenario in which a bus obstruction impacts a user located at a fixed position for e.g. user at a bus stop. Other random users are considered in the scenario (for generating interference); 200/km² is considered. The mean SINR and the mean inter-cell interference simulated for the fixed user without the bus obstruction are 21 dB and -143 dBm respectively, while the connection is provided by the small-cell located to the east of the user. Fig. 4 shows the impact of the bus obstruction at various positions of the bus in front of the user. The fixed user is located at central position (0 m) and the front of the bus is aligned to the user at this position. The bus obstruction is the strongest at the position -6 m when the centre of the bus is aligned with the user. A reduction in SINR level by 20 dB (upper limit) is seen caused by the large vehicle obstruction. This also leads to higher interference levels when the dominant path is obstructed by the bus. The scenario stresses how in-street obstruction can dramatically change the radio conditions, cell assignment and the network performance.

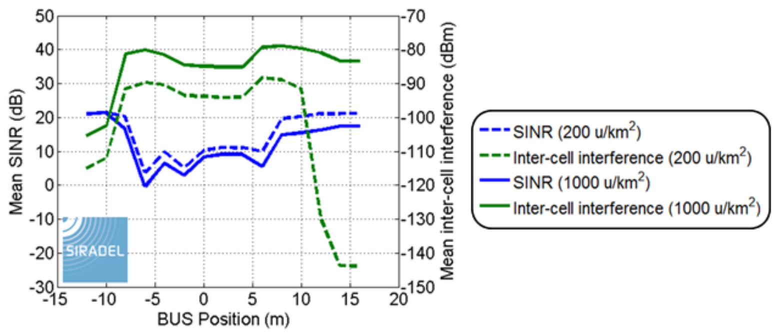

Fig. 4. Effects of large vehicle obstruction on a fixed user.

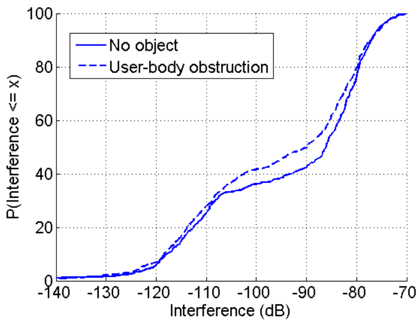

Fig. 5a. CDF of Inter-cell Interference levels with two small-cells.

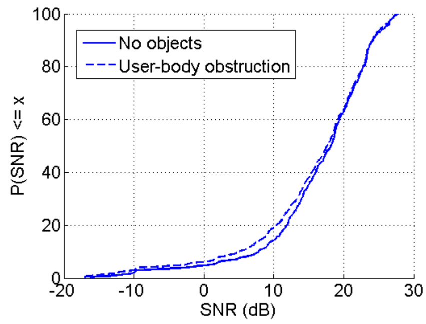

Fig. 5b. CDF of SINR levels with two small-cells.

To analyze the impact of the user-body self obstruction, the body model described in 2b is applied to the users dropped in the street containing the two small-cells. Note that the large vehicle and fixed user scenario is not used here. Fig. 5a and Fig. 5b show the CDF of respectively the inter-cell interference levels and the signal-to-interference-plus-noise-ratio (SINR), with and without user-body consideration. The user-body obstruction leads to lower interference levels. The median interference reduces significantly by 6.7 dB while the most critical interference levels (at highest percentiles) exhibits lower variations; i.e. 0.6 dB at the 90% percentile and lower than 0.1 dB at the 95% percentile. The SINR CDF exhibits degradation caused by the signal reduction; the SINR reduces by 2.9 dB and 0.5 dB for respectively the 10% and 50% percentiles. But there is insignificant degradation for the 90% percentile. The impact of the body obstruction has been partly mitigated via two mechanisms: 1) a strong SNR reduction leads the user to switch to the other cell; 2) when interference is greater or similar to the noise level, the reduction of the interference levels may compensate part of the signal decrease. This is particularly true for users for which the body severely obstructs the closest small-cell; those users move to the other cell providing lower signal strength; but then the interference that is coming from the closest cell is negligible. Finally, the simulation results indicate that a major effect of the user-body obstruction is higher inter-cell isolation.

The basic studies presented in the two-cell scenario were chosen to properly validate, illustrate and make understandable the user performance evolutions. The whole network simulation deals with a more complex scenario.

ii. Whole network simulation

The effect of the user-body blockage and interactions with large vehicles is now assessed through the whole small-cell network. The density of active users is 1000 users/km^2. The network performance is computed in three different scenarios: 1) no stochastic component; 2) consideration of the user-body obstruction; 3) consideration of both user-body and vehicles together. The results for respectively the Inter-cell interference and the SINR are given in Fig. 6a and Fig. 6b.

The reduction of the inter-cell interference due to the user-body blockage is confirmed in Fig. 6a, with an average decrease of 1.9 dB. As observed in the two-cell scenario, this positive effect, as well as the optimal cell selection process we consider in the simulation, makes the SINR degradation quite limited. As illustrated in Fig. 6b, the 10% SINR percentile decreases by 1.1 dB while the median SINR decreases by 0.2 dB due to body obstruction. Adding the vehicle obstruction has an insignificant impact on link quality. Actually the impact of vehicle obstruction is local only and has been compensated by two mechanisms (the same as for the body obstruction but at a higher degree): 1) The obstruction of the dominant path can be partly mitigated by the system by pointing the antenna towards another path; 2) The reduction of the SINR leads the user to switch to the other cell and benefit from significant interference reductions due to vehicle obstruction. This latter mechanism is emphasized in the streets where small-cells are distributed alternatively along each sides of the street. Remark that as observed in the single bus obstruction scenario investigated in [7], there are some specific cases where link quality may dramatically degrade but their occurrence appears to be small.

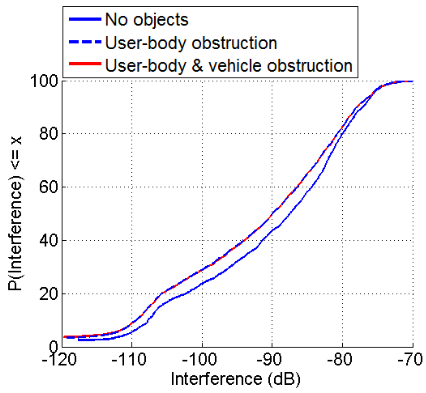

Fig. 6a. CDF of Inter-cell Interference levels on whole network.

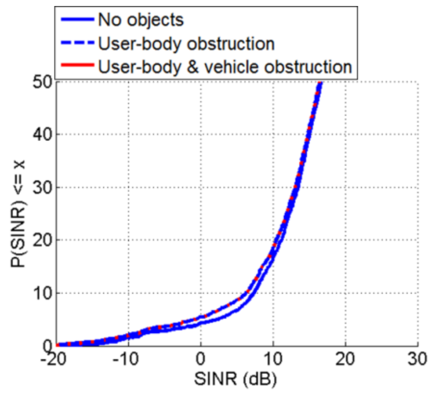

Fig. 6b. CDF of SINR levels on whole network.

4. Conclusions

A ray-based channel model is applied on a geographical map data enriched with random non-static objects. The goal is to produce realistic channel realizations in the context of a dense outdoor 60-GHz small-cell network evaluation. The presented study illustrates the impact of random large vehicles and randomly-oriented user-bodies into different scenarios.

The user-body is shown to sometimes bring positive effect, with stronger inter-cell isolation. Besides, the degradation on the useful signal strength is not affecting too much the global network performance, as soon as the victim users can switch to another cell with no body masking. The obstruction by the user-body and vehicles finally leads to a quite limited reduction of the SINR. Significant degradation occurs only on the very worse-served users: 1.1 dB on the 10% percentile; and 0.2 dB on the median percentile. Analysis will continue in future studies in order to better identify, understand and model the main non-static factors that should be considered in mmWave network design. Based on the results, it can clearly been seen that the impact of large vehicles in the street can be reduced by physically placing the small-cell base stations on opposite sides of the streets in an asymetrical manner.

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