Simulated Propagation Properties for Future Outdoor sub-THz Networks

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***Abstract*— The sub-THz spectrum is today one of the most promising technologies to provide large network capacities beyond the 5G era. The modelling of the propagation channel is needed for research and test, but the channel understanding is still limited. One of the key challenges at these high frequencies is the large propagation loss, in particular the impact of vegetation on outdoor links. In this paper, a ray-based tool validated at millimeter-wave frequencies is used to analyze and characterize the outdoor propagation channel at 150 GHz. Different environments like urban canyon, residential and a wide main street are considered and accurately modeled with LiDAR data, in order to assess the propagation properties for several outdoor antenna configurations: mesh backhaul, Fixed Wireless Access (FWA) and mobiles access. Such simulation studies in conjunction with measurements can lead to better channel understanding. Interesting perspectives on the validation of sub-THz use cases and deployment strategies can be formed.**

Keywords*— *Sub-THz, channel characterization, ray-based model, LiDAR data.

I. INTRODUCTION

The release and commercialization of the 5G NR, IEEE 802.11ad and 802.11ay standards utilize millimeter-wave (mmWave) frequencies and larger bandwidths to provide higher promised data-rates. As the current standards continue to evolve with stronger requirements and new use cases, a clear direction in beyond-5G research lies in the exploitation of even higher frequencies, i.e. referred to as the sub-THz spectrum from 100 to 300 GHz, or the THz spectrum above 300 GHz [1] [2]. The key limitation at such higher frequencies is the restricted propagation distance due to the frequency-dependent propagation decay, high blockage and penetration losses. Indoor scenarios at such high frequencies are limited to a single room, while mobile access in outdoor scenarios requires high network but cannot offer seamless connectivity. Fixed direct-path applications like point-to-point (P2P) backhaul links and Fixed Wireless Access (FWA) are more suitable. In areas without fiber connectivity, multi-gigabit data rate wireless backhaul links can provide a less expensive alternate solution, which can be deployed with limited civil work and shorter timelines compared to optical fiber. FWA could provide last-mile broadband access to Customer Premise Equipment (CPE) at the building façade or rooftop, from which lower frequency access can be made available indoors. Utilizing the existing dense street furniture like light poles, the backhaul links can be quickly setup with good propagation conditions.

The characterization and modeling of the in-street backhaul at 60 GHz is still in initial stages today [3] and the channel at 150 GHz is mostly unexplored yet. However the in-depth analysis and characterization of such channels is required in order to design appropriate physical-layer technologies, elaborate communications protocols, assess the new systems performance, formulate deployment rules and create reliable radio-planning tools. In [4] measurements at 60 GHz, outdoor backhaul P2P links were obtained using Terragraph nodes as part of the Telecom Infra Project (TIP) [5]. The measurements were performed on the Darmstadt campus of Deutsche Telekom, with different kinds of building façades, medium tree density, and some street furniture. These measurements were used to characterize the propagation properties, but also compare and validate the simulations of the ray-based Volcano model [6] [7]. The simulations were performed using highly accurate representation of the geographical environment, based on LiDAR (Light Detection and Ranging) point cloud data that was collected at street level at the same time as the measurements, i.e. in the summer season when the vegetation contains most of the foliage. The point cloud data was obtained with a density and a measurement protocol that guarantee a precise 3D representation of most trees located in the street.

The measurements were employed for validating the model and adjusting some of its parameters e.g. for vegetation losses, while the measurements and simulations were together analyzed in order to understand the main channel properties by close inspection in the simulation environment. Besides, the simulator provides a very convenient way to explore the channel characteristics in additional non-measured scenarios, e.g. to get a more global insight on the urban backhaul link conditions. This could easily be extended to higher frequencies as well, as the same physics are applied to the environment; the prediction changes occur in the interactions with the environment such as transmission losses, reflection and diffraction losses etc., provided accurate material or medium properties are available.

In [8] the authors explained what simple assumptions have been made to extend the ITU material properties beyond the existing 100 GHz limit until 150 GHz. This extended ray-based Volcano model is utilized here to complement the initial analysis [4] and investigate other scenarios at 60 and 150 GHz. Different propagation environments have been considered: urban canyon with limited vegetation, residential with dense non-uniform vegetation, and a main street with uniform distribution of vegetation. Three potential sub-THz

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use cases have been reproduced in those environments and studied: dense mesh backhauling based on multiple point-to-point (P2P) links; fixed wireless access towards the building façades; and in-street mobile access. Note this latter use case is not an *a priori* target for outdoor sub-THz deployments, but it is worth getting a better insight in it. Four different heights of nodes have been compared for backhaul and FWA use cases. Finally, a combined perspective is provided by averaging the characteristics over the considered environments. The followed methodology is summarized in Fig. 1; step ❶ was reported in [4] leading to the validation of channel model at 60 GHz, while steps ❷ and ❸ rely on the ray-tracing capability to adapt; their results are described here below.

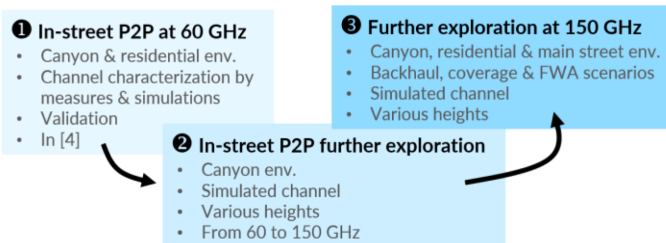

Figure 1: Study main principles.

The paper is organized as follows. Section II gives a description of the different scenarios used and the simulation setup. The ray-based channel model is introduced in Section III. The channel characterization of the urban canyon case at 150 GHz is provided in Section IV. Then the different simulation results for the P2P backhaul links, the mobile access coverage, and the FWA façade coverage are provided in Section V. Some perspectives and conclusions are then drawn in Section VI.

II. Scenario and Setup

The present study is based on the same scenario as measured and simulated in [4]. The measurement campaign was performed at 60 GHz using Terragraph nodes from the Facebook connectivity initiative [5]. The analysis and validation of the mmWave urban channel model was supported by the accuracy of the obtained same-season LiDAR data in the measurement area. The display of 3D LiDAR point cloud allows for a very accurate and visual understanding of the in-street blockage situations. And its usage by the Volcano ray-based model permits for automatic detection and computation of obstruction losses.

Point-to-point backhaul links in two different environments; urban canyon and residential were considered. Apart from the blockage due to the high frequency, one of the key factors for the channel sparsity observed in [4] was attributed to the height of the nodes used. The nodes placed at 3 m above the ground had significant blockage through the vegetation, particularly in the urban canyon environment. Investigating how the blockage conditions evolve with the height of nodes and at higher frequencies (sub-THz spectrum) would have been complex, long, and expensive if based on measurements. But using the LiDAR data and the validated ray-based tool, an extension of the initial scenario is easily feasible; it is explored in the present paper, including additional heights and node positions.

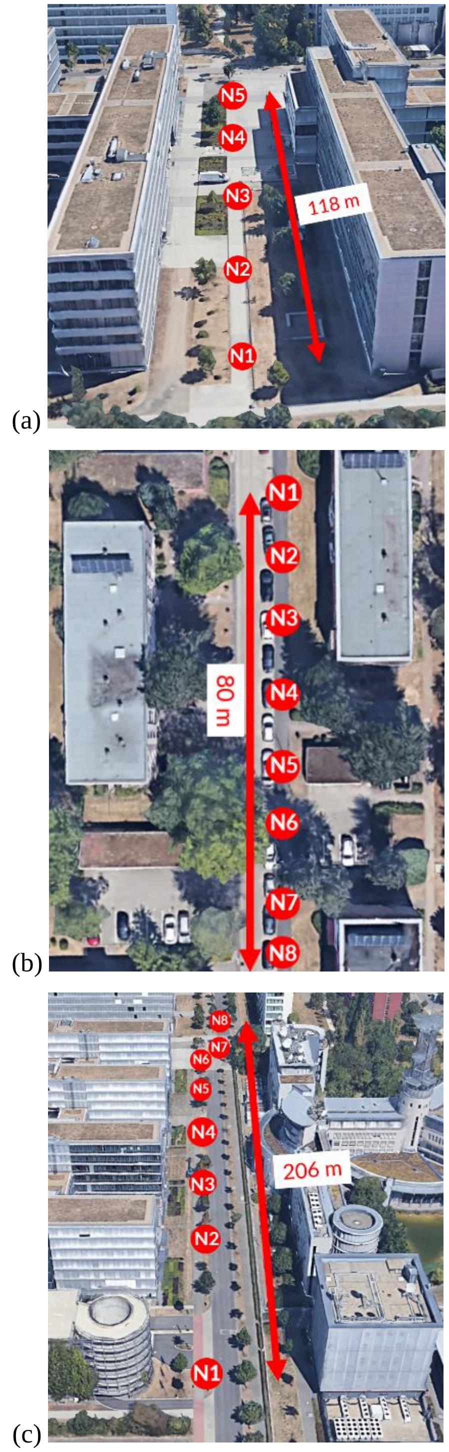

Figure 2: Scenarios in (a) urban canyon, (b) residential, and (c) main street environments.

Three locations with different properties have been considered for the further analysis and channel characterization. The first location considered is the urban canyon environment, which is a street in between two multi-floor buildings with a mixture of glass and metallic frame façade, separated by a distance of 35 m. The length of the street is 150 m-long and consists of some trees and bushes as shown in Fig. 2. The positions of the 5 nodes placed in the area are on average separated by 30 m. In case of the point-to-point scenario, the distance between the links is considered from the first node (marked N1 in Fig. 2) and the other individual nodes. Therefore, the link distances vary with each pair of nodes ranging from 27.8 m to 118 m.

The second location considered is a narrow residential street with thick vegetation, different types of trees, and different heights, as shown in Fig. 3. Apartment buildings with three floors are located on both sides of the street consisting of a complex façade with large windows, concrete walls and balconies. Other in-street objects like sign posts and street lights are also present at regular intervals in the area. The positions of nodes are considered along a sidewalk located 7 m from the closest building wall. A total of 8 different node positions have been considered in this environment at an average distance of 10 m from each other. For the P2P case, the node N1 is considered as the Tx and the remaining nodes as receivers, therefore consisting of varying link distances, similar to the previous location.

The third location is along a wide urban main street with two-lanes for traffic with vegetation lined on both sides of the road as shown in Fig. 2(c). There are also pedestrian paths on both sides of the road. The street is approximately 45 m wide, almost twice as wide as the first location in the urban canyon. The street is about 300 m long and the nodes are placed 29.3 m apart on average on the existing street light positions (found from the LiDAR data).

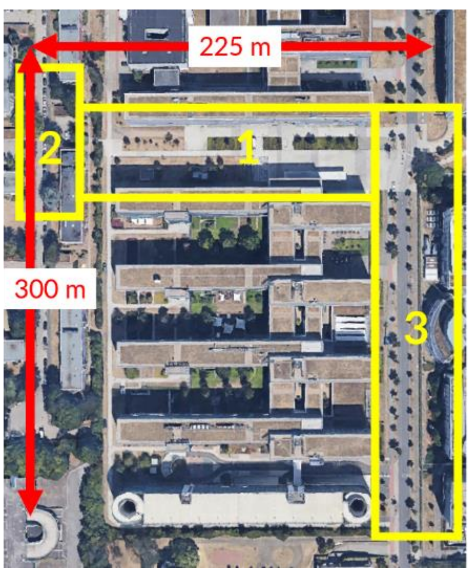

Figure 3: Considered area including all three scenarios.

All three different locations have been considered together to obtain a network of nodes as illustrated in Fig. 3. At each node position in all the three streets, four different heights are considered at 3 m, 6 m, 9 m and 12 m. The large multi-floor office buildings in both urban canyon and the main street remain higher than the highest considered node height. In the residential scenario, there exist some buildings shorter than 12 m however most of the apartment buildings are higher than the highest considered node height.

III. Ray-based sub-THz channel model and parameters

The Volcano ray-based tool [6] creates multi-paths caused by various channel phenomena like reflection and diffraction on building façades and ground. In-street objects like vegetation or urban furniture generates blockage or attenuation, and above-clutter diffraction. When available, the LiDAR point cloud data is used to detect the in-street obstructions (intersection between the point cloud and the clear ray trajectory) and calculate an accurate penetration length in case of a through-foliage transmission. The tool has been adjusted and validated with various measurements at different mmWave frequencies over the years in different scenarios. Since measurements are mostly only available for frequencies upto 100 GHz, an extension of the channel model in the sub-THz has been proposed in [7] based on some assumptions (materials, vegetation loss), which is convenient for preliminary investigations.

A vegetation linear loss of 5 dB/m was tuned from cross-analysis of the measurements and simulated paths in the previous 60-GHz validation study [4]. This value has been extrapolated to 12 dB/m at 150 GHz, following the same tendency (but not same absolute values) as in the ITU recommendations [9].

We have supposed clear weather condition, i.e. no rainfall attenuation, as the time availability will be investigated in a later step. Finally, note there is no car blockage or scattering considered in the present study, where the minimum height of nodes is 3 m.

Three deployment scenarios have been evaluated in each environment: 1) Mesh backhaul, being formed of dense pole-to-pole line-of-sight (LoS) links, as studied in the measurements; 2) FWA with access points positioned on poles and user devices a.k.a. CPE installed on the building façades; and 3) Mobile access with same FWA access points but user devices distributed in the outdoor environment at ground level. A link budget summary for all the scenario parameters is presented in Table 1, where a 1 GHz signal bandwidth and the polar demodulation described in [1, section 4] are assumed. Different kinds of prediction modes have been performed to match each scenario's specificity: point-to-point (P2P), point-to-façade (P2F), or area coverage, as available in the tool.

Table 1: Scenario parameters.

Parameter	Backhaul	FWA	Mobile Access
Node/AP height	3, 6, 9, 12 m		12 m
CPE/UE height	N/A	3 m	1.5 m
Bandwidth	1 GHz		
Carrier	60, 150 GHz	150 GHz	
Tx power	0.1, 1 W	0.1 W	
Tx antenna gain	25 dBi		
Sensibility at the Rx input	-73.2 dBm		
Rx antenna gain	25 dBi	15 dBi	
Sensibility at the Rx antenna input	-98.2 dBm	-88.2 dBm	
Add. loss	3 dB		
Weather	Clear		

The in-street blockage differs significantly from one deployment scenario to the other, but also from one environment to the next. The vegetation in the urban canyon environment is smaller and sparsely spaced whereas the residential area is densely covered with vegetation of different types of trees with varying heights and foliage cross-sectional width. In the main street environment, the vegetation is mostly uniformly distributed along the road with similar heights and types of trees. This environmental diversity was considered on purpose. And section V is gathering the results from the three different environments to get average and fair statistics.

IV. SUB-THZ CHANNEL CHARACTERIZATION IN THE URBAN CANYON CASE

The network of nodes in different environments described in Section II and the ray-tracing tool described in Section III have been used together to analyze both the 60-GHz and 150-GHz outdoor backhaul channels, as well as the sub-THz FWA and mobile access propagation ranges.

The differences in the received powers and number of significant paths when increasing the height of the nodes from 3m to 6m for 150 GHz point-to-point links in the urban canyon environment is shown in Fig. 4 and 5. At the mmWave and sub-THz frequencies, the blockage and vegetation linear losses have a significant impact on the propagation environment. The variations in the received power based on the cross-sectional width of the vegetation through which propagation occurs can be significantly different. Some trees are widest (having most foliage) towards the lower parts of the foliage and narrower as the height increases. Due to this, the propagation through the vegetation can have significantly different losses depending on the height. If the considered height is higher than the locally available vegetation or below the foliage, the losses are minimized. A reduction in the linear losses can also be expected in the winter season when the vegetation has lost its leaves.

In Fig. 4, the nodes are located at a height of 3m and even though the vegetation mostly consists of small trees and bushes in this urban canyon environment, there is a significant reduction in the received power components from all the paths apart from the direct LoS path. Although the reflection loss at higher frequencies does not significantly change, the blockage caused due to the vegetation and other in-street objects deteriorates the propagation, making it sparse. Considering only a single height (at which there is maximum blockage), conclusions like a highly sparse channel could be made. However, depending on the local environment and blockage conditions, the tradeoff between the ideal node height providing better connectivity and practical deployment issues must be considered. In particular, the presence of multiple significant paths may be an advantage for spatial multiplexing, or resilience in the face of interferences. Ray-based tools like [6] provide the possibility to analyze and evaluate the channel conditions for a given environment with limited effort, and automatically decide best options.

The number of paths significantly increase with the height of the node as illustrated in Fig. 4-5. While the propagation may be concluded to be highly sparse at height 3 m, due to the vegetation blockage, the same environment can be observed as a canyoning situation with a few strong reflections at a different height.

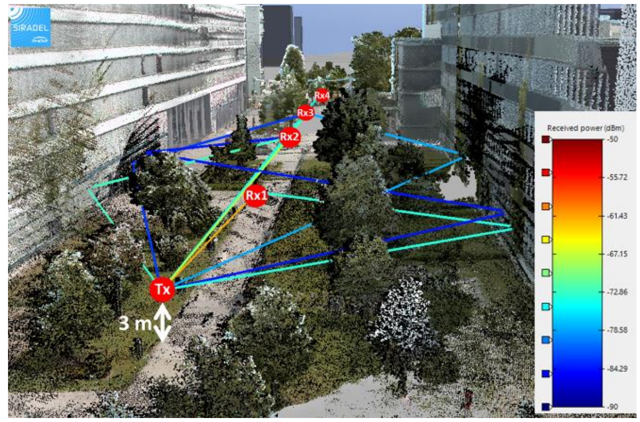

Figure 4: Significant simulated paths for the urban canyon P2P links at height 3 m.

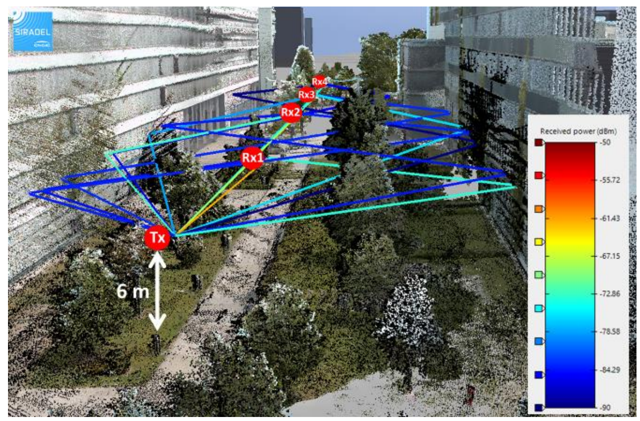

Figure 5: Significant simulated paths for the urban canyon P2P links at height of 6 m.

V. RAY-BASED SIMULATION RESULTS

All the 20 nodes described in Section II have been utilized to obtain three different results based on backhaul, fixed access and mobile access links. P2P, P2F and coverage maps have been respectively used to compare the performance of different node heights. To calculate the number of significant paths for each link, a receiver sensitivity of -98.2 dBm is considered, which corresponds to a spectral efficiency 0.6 bps/Hz.

A. *Outdoor point-to-point backhaul links*

The ideal height of the nodes can vary from one scenario to another and even from one node to another depending on the immediate obstacles around the nodes. Due to the higher path losses, the importance of significant propagation paths which have the strongest power after the direct LoS path like reflections increases. Not just to provide a connection if the direct-path is blocked but also to provide spatial diversity of reception. If these paths are significantly attenuated, it has a major impact on the propagation channel.

Different link lengths are considered by using the first node (N1 in Fig. 2) in each environment as a transmitter and the other nodes as receivers (N2-N5 in Fig. 2). The total number of nodes considered are 20 and the number of links are 3, 7 and 7 respectively for the urban canyon, residential and main street scenarios with a total of 17 P2P links. Transmit powers corresponding to 0.1 W (20 dBm) and 1 W (30 dBm) are plotted. The average of the total number of significant paths for each link is plotted against the height of the nodes in Fig. 6. As the transmit power is increased, more paths through the same vegetation become visible at the receiver. In the main street (Fig. 2(c)), the nodes are located on existing light poles and between each light pole there exists a tree. At a height of 6m, the vegetation losses are the highest due to the largest vegetation cross-section along the direct LoS path. This results in an average of just 1.3 and 1.4 significant paths at this height for respectively 20 dBm and 30 dBm transmit powers. Finally, Fig. 6 shows significantly better channel diversity statistics at the lowest (3 m) and highest heights (9 m and above). The plot also indicates that the multi-path diversity reduces by 0.3 in average for same link budget at 60 and 150 GHz, with a maximum of 0.7 at height 6 m.

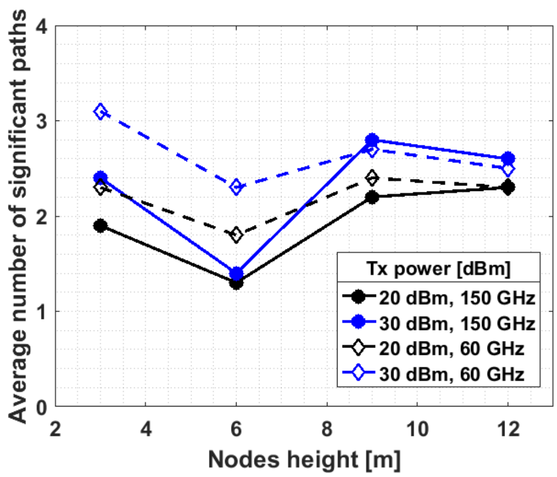

Figure 6: Average number of significant paths per P2P LoS link.

B. Outdoor mobile access coverage

A coverage (or received power) map is computed around each node, as illustrated in Fig. 7, for an outdoor mobile device at 1.5 m above ground. Fig. 8 shows the average of the single-node covered surfaces for a varying received power threshold and for different node heights. The covered areas obtained from the link budget given in Table 1 is highlighted by the vertical dotted line.

At the highest received power thresholds, the coverage is due to the direct LoS path in the immediate vicinity of the node. As the distance increases, corresponding to a larger covered area, the probability of blockage is greater. By consequence, the rate of additional coverage surface due to every 1 dB sensibility gain degrades very rapidly. The best coverage is always obtained from the nodes at height 3 m whatever the receiver sensibility is, first because those nodes are closer to the user equipments at 1.5 m, but also due to the favorable propagation met below the foliage. The coverage may locally be improved by using a node height of 12 m, as highlighted by the red circles in Fig. 7; this occurs when the obstructing foliage is low; nevertheless, if considering a receiver threshold of -88.2 dBm (link budget given in Table 1), the coverage at 12 m is globally 7% lower than the coverage at 3 m. Those results demonstrate the significant impact of vegetation at higher frequencies. It also stresses the sensitivity of the propagation simulations to accurate representation of the environment; we believe a realistic sub-THz channel model needs to integrate some geographical data and some physics into it.

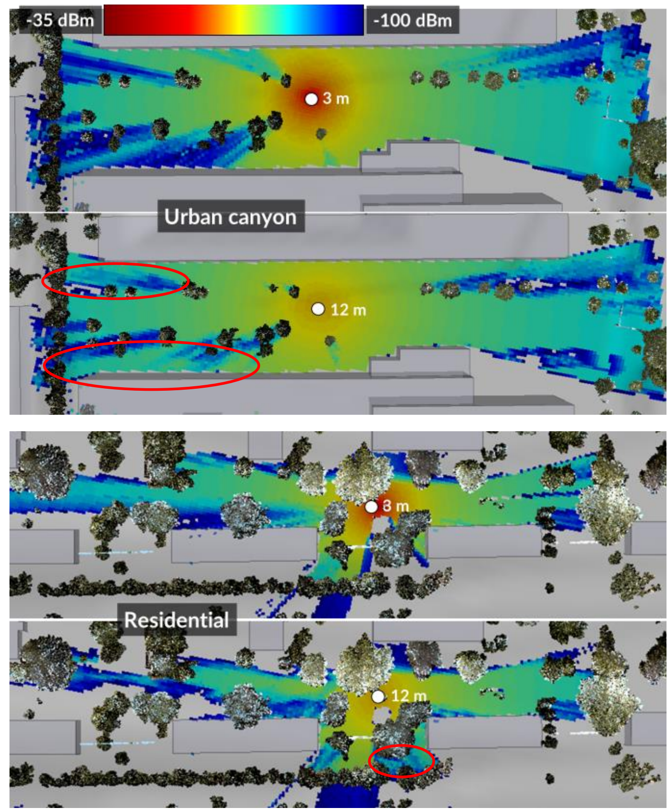

Figure 7: Rx power map around two different nodes.

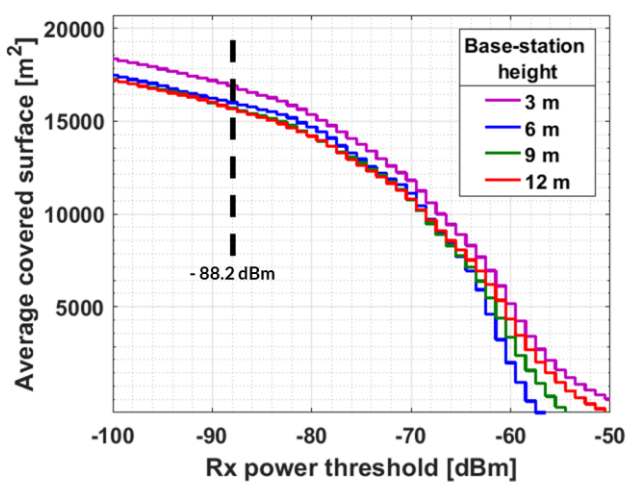

Figure 8: Average covered area per node for different heights.

C. *Fixed Wireless Access coverage*

Another promising outdoor application of the sub-THz frequencies apart from the point-to-point backhaul links is Fixed Wireless Access (FWA). The same 20 node positions have been utilized and the coverage is evaluated as obtained at 3 m above ground along the building facades. Fig. 9 shows the average of the covered façade length for each single-node and for a varying received power threshold considering different node heights. The coverage at the highest received power thresholds is found to be better for lowest node heights (maximum 9 m) due to reduced blockage probability and smallest vegetation transmission lengths in the node vicinity. High node elevation is not an advantage, because most CPE's are located behind trees and below foliage. At lower received power thresholds, the nodes at 12 m still suffer from a more severe attenuation at the CPE's located behind a row of trees, but do benefit from a better propagation above trees in some directions. Finally, the intermediate heights appear as slightly less advantageous.

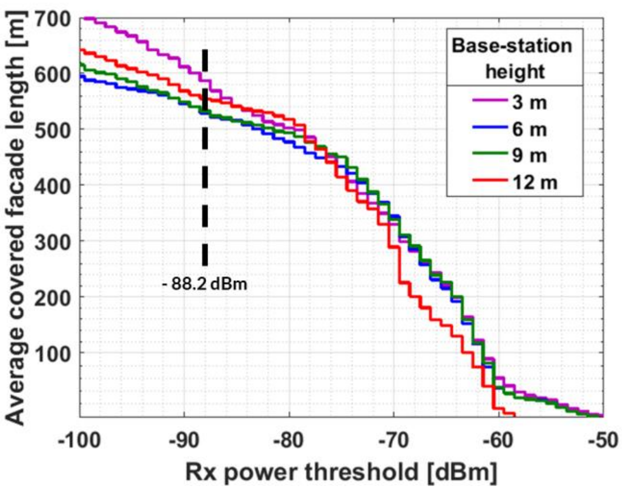

Figure 9: Average covered facade length per node for different heights.

VI. CONCLUSIONS AND PERSPECTIVES

As the need for larger bandwidths and capacity drives beyond-5G applications towards the promising spectrum available in sub-THz bands, better understanding of the channel, characterization, validation and evaluation of such high frequency channels will be required. Due to physical constraints in measurement campaigns, it is often very difficult to obtain a holistic perspective of a channel, especially new spectrum that has not yet been explored significantly. The validated tools can then be exploited to explore other scenarios utilizing the same physics phenomenon like analyzing the height of the nodes to better understand the channels.

In this paper, tools validated with measurements at 60 GHz have been used to further understand the channel and also utilize extensions to analyze propagation channels at 150 GHz. Both backhaul and access links have been considered at 4 different heights. Various scenarios like urban canyon, residential and main street have been considered with different link distances and situations; the channel does not necessarily benefit from better conditions at higher node heights (as usually observed at lower frequencies) can behave significantly different depending on the height of the nodes, power and angular sensitivity of the receiver and the considered transmit power. Vegetation is a significant cause for the in-street blockages at higher frequencies and accurate representations using for instance LiDAR data must be considered for physical-layer evaluations.

ACKNOWLEDGMENTS

The channel measurements were collected by Deutsche Telekom and granted as part of the Channel Sounder Program of Telecom Infra Project (TIP). The research at 150 GHz received funding from the French National Research Agency (ANR-17-CE25-0013) within the frame of the project BRAVE.

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