Analysis of Vegetation and Penetration Losses in 5G mmWave Communication Systems

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***Abstract*— The 5G network has been intensively studied within the early deployment stages as an effort to match the exponential growth of the number of connected devices and users, alongside with their increasing demands for higher throughput, bandwidth, and lower latency. Knowing that most of the frequency spectrum below 6 GHz is saturated, it is not feasible to rely only on the traditional frequency bands that are currently in use. Therefore, a promising solution to combat the insufficient frequency spectrum is to adopt new frequency bands for next-generation mobile communication systems. The primary effort has been focused on utilizing the millimeter-wave (mmWave) bands as the most promising candidate for the frequency spectrum. However, even though the mmWave frequency bands could fulfill the desired bandwidth requirements of 5G, it has been demonstrated to endure several issues such as scattering, atmospheric absorption, fading, and especially penetration losses compared to the existing sub-6 GHz frequency bands. Then, it is fundamental to optimize the mmWave band propagation channel to facilitate the practical 5G implementation for the network operators. In this paper, we simulated different scenarios in order to study the vegetation and penetration loss in 5G systems. Vegetation loss will be studied using the 28 GHz bandwidth and for the penetration loss we will study soft materials <15dB and hard materials >20dB.**

Keywords— 5G; mmWave; propagation channel; path loss; channel characterization, vegetation loss, penetration loss

I. Introduction

The 5G network is composed by a set of technologies corresponding to the fifth generation of the standard for mobile telephony. It is validated by the International Telecommunication Union (ITU) and the 3GPP (3rd Generation Partnership Project) and has well defined performance requirements. Specifically, in order to achieve the high user demands, new high-frequency spectrum bands over 6 GHz are being taken into consideration. An example is the millimeter waves (mmWave) that are known for delivering extremely large bandwidth [1]. The term mmWave indicates the high-frequency band ranging from 24 GHz up to 100 GHz, which has a very short wavelength. The mmWave technology is a fundamental part of 5G systems that is intended to be utilized for seamless communications. mmWaves have been investigated in many fields and through different use-cases, including the average probability optimization of 5G cellular systems through flexible hybrid mmWave spectrum slicing-sharing access approach [2], the designing of robust channel estimation schemes, the effect of beamforming on this technology, as well as the investigation of channel parameters and throughput estimates for mmWave networks [3]. However, there are technical challenges that are associated with the mmWave frequency high-band.

The mmWave signals are sensitive to obstructions in real life environment scenarios due to their smaller wavelength compared to the dimensions of objects. Consequently, it is of major relevance to analyze these effects on the system, such as body shadowing, building penetration and foliage attenuation when deploying mmWave networks [4]. For these reasons, a thorough understating of the propagation channel in the mmWave bands plays an important role of achieving the optimum design of cellular networks and the cost-effective placement of Base Stations (BSs). The channel characteristics of mmWave cellular systems are site-specific because of their vulnerability to propagation effects.

Vegetative environments causes the attenuation of radio frequency waves, whereby the attenuation increases with frequency. 5G bands aim to operate in very high frequencies, thus creating an emphasis to study the vegetative propagation properties of these signals. The branches and leaves must be taken into account because they can cause signal attenuation due to scattering and absorption [5].

In this paper, we study the vegetation loss for the 28 GHz frequency band taking into account different scenarios, such as in-leaf, out-of-leaf, Seville. We also evaluate the RF penetration loss for different materials, including bricks. We will present a comparation between the values obtained for both the vegetation and penetration loss.

The remainder of this paper is organized as follows, Section II presents the propagation losses present in 5G systems and Section III depicts the simulation parameters and results obtained. Lastly, Section IV delivers the conclusions of this paper and the future work.

II. Propagation Losses

Propagation losses suffered by mmWave communications are much greater than losses suffered by lower frequencies. There are many types of propagation losses seen in 5G systems, each one being described individually below [6].

A. *Atmospheric gaseous losses*

While traveling through the troposphere layer, radio waves interact with gas molecules such as oxygen (O2), nitrogen dioxide (N2), and water vapor (H2O). This may or may not be a lossy interaction. Signal attenuation is the result of any contact that results in energy loss. At the resonance of molecules, when their electrons begin to delocalize, there are

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significant losses. When an asymmetric (H2O) molecule is put in a strong electric field, for example, it prefers to align in the direction of least potential with respect to the field. This process leads to energy loss. However, absorption of electromagnetic energy happens when it equals the quantum excitation energy of molecules. The resonance at 300 GHz is caused by the gaseous absorption of water vapor and oxygen in the environment. The strong resonance band for oxygen and water vapor lies between 57 and 60 GHz and 22 GHz, respectively. The attenuation depends on the quantity of water vapor in the atmosphere [7]. These losses are larger at certain frequencies that correspond to the mechanical resonance frequencies of the gas molecules.

B. *Reflection*

Reflection occurs when an electromagnetic wave impacts an object with unusually large dimensions relative to the wavelength of the propagating wave. mmWaves are reflected by surfaces of objects such as furniture, walls and buildings. When a radio wave encounters a material with varied electrical characteristics, it is partially reflected and partially refracted. The reflected energy and refracted energy rely on the medium's material qualities and the physical parameters of the wave, such as frequency, polarization, and incidence angle. For the case of the dielectric medium, some of the wave is reflected back to the first medium. If a medium is an ideal conductor, the quantity of energy reflected depends on the wave's polarization [8].

At higher frequencies, a reflecting surface seems rougher than at lower frequencies. This causes the signal to reflect diffusely. Thus, at mmWave frequencies, the effect of specular (direct reflection off a smooth surface) reflection is less, and signals are mostly dispersed at reflecting surfaces, resulting in less reflected power at the receiver.

C. *Vegetation loss*

One of the most significant impediments in mmWave propagation is attenuation or occlusion induced by vegetation. This loss is known as vegetation loss. The many components of the foliage consist of leaves, branches, tree trunks and twigs that are dispersed at random locations. As the size of the leaves approaches the size of the wavelength, signal penetration through the leaves decreases, while scattering from the leaves rises [9]. Due to multipath dispersion, diffraction and reflection, radio waves traveling in foliated environments, such as forest medium, lose energy.

D. *Penetration loss*

Signal attenuation produced by its transmission through a substance is known as penetration loss. It is the difference between the power received in free space and the power received with an obstruction between the transmitter and receiver. The deterministic value of the received power is computed keeping in mind that Excess Channel Loss (ECL) is the attenuation added to the communication channel due to the inclusion of the obstructing material between the Transmitter (Tx) and Receiver (Rx), as depicted in figure 1 and expressed mathematically in equation (1):

$$P_R(d) = P_T + G_T + G_R - 20\log\left(\frac{4\pi d_0}{\lambda}\right) - ECL \quad (1)$$

, where P_T and P_R are the transmitting and receiving power in dBm, G_T and G_R are the gain of transmitting and receiving antennas in dBi, λ is the wavelength (10,71 mm at 28 GHz and 7,89 mm at 38 GHz) [10]. The reference distance d0 was defined as 0,75 m, which is large enough to ensure that characterization analyses occur in the antenna Fraunhofer region (far-field).

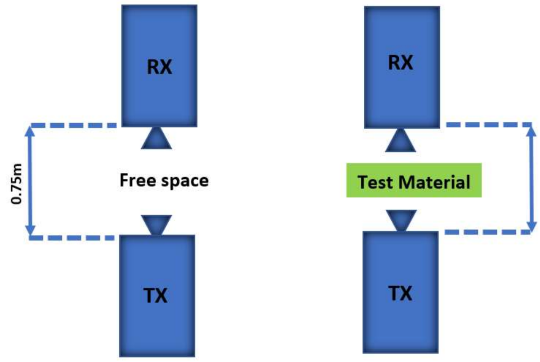

Figure 1: Penetration loss testing method.

E. *Scattering*

Due to nonuniformities in the medium through which the signal propagates, scattering is a physical phenomenon in which the signal deviates from its original course. Models of reflection and diffraction fail to anticipate the quantity of energy received by the receiver. This is because houses, trees and other structures distribute energy in all directions.

Radiation that is reflected departs from the angle anticipated by the law of reflection. Specular reflections are radiations that obey Snell's law of reflection from smooth surfaces and stay as unscattered reflections. On the other hand, dispersed reflections refer to reflections from rough surfaces that undergo dispersion [10].

F. *Diffraction*

During propagation in a homogeneous medium, radio waves with a lower frequency are more likely to deflect around obstacles. Energy is received at the receiver even though there is no Line of Sight (LOS) channel between the transmitter and receiver due to diffraction. Once a radio wave collides with an obstruction, its amplitude and phase change, and it reaches the shadow zone, reducing the intensity of the received field. Due to its high signal-generating intensity, the diffraction field continues to exist.

Signal diffraction relies on the size of an obstruction and the signal's wavelength. Both metrics should typically be equivalent. This is why transmissions with lower frequencies are readily diffracted over big, smooth barriers such as hills. In the absence of a LOS path between the transmitter and receiver, reflections will contribute significantly to the received power since diffraction of mmWave signals will be minimal due to their shorter wavelength.

III. SIMULATION PARAMETERS AND RESULTS

In this section we present the simulation parameters adopted for this work. All the computations were conducted using Nokia's internal simulator with MATLAB, a tool used for dimensioning. For the purposes of running the simulations, an environment that replicates outdoor propagation was selected. The 5G antenna was installed at a height of 30 meters in this particular case. It was decided that the antenna coming from the user equipment should be at a height of 1.5 meters. Twenty meters is the typical width of a city street, while eight meters is the typical height of a structure. The simulations were being carried out in a metropolitan setting.

Initially, we investigate the vegetation loss for a variety of models, including ITU-R, MED (d >= 14m), COST 235 (out-of-leaf), COST 235 (in-leaf), FITU-R (out-of-leaf), FITU-R (in-leaf) and Seville. ITU-R foliage attenuation model is a model proposed by the International Communication Union Radiotelecommunication Sector [11]. The values of the 3 components proposed by them can be found in the Table 3. The Weissberger (MED) model estimates the path loss caused by vegetation in a point-to-point vegetation link. This model is applicable only when the transmission path is LOS, otherwise it can not be applied. This model have 2 values for each of the three components, depending on the depth of foliage around the path [12]. When calculating using the formula presented below it can be seen that the results are very similar, and due to that only one curve will be represented on the graph. This will be representing the average values between these two scenarios. COST235 is another path loss scenario regarding the foliage attenuation. COST235 was developed based on measurements of millimeter waves from 9.6GHz to 57.6GHz in a small forest (d < 200m). It can be calculated for two foliation states, in-leaf scenario and out-of-leaf scenario [13][14]. The following model is very similar to the ITU-R, being a model derived from it. It is called FITU-R, which means Fitted ITU-R. FITU-R is based on VHF to millimeter wave measurement data across short foliage depth (maximum 400m). This model has again two foliation states, in-leaf and out-of-leaf [14]. Seville and Craig is the last model studied. It is a nonzero gradient (NZG) model at millimeter wave for high capacity point-to-point link. When trees or other plants can be seen along the propagation route, additional foliage loss should be taken into account when figuring out the link budget so we can obtain satisfactory and real results. It can be calculated using the below formula (2):

$$L(dB) = xf^{y}d_f^{z} \tag{2}$$

where f is the operating frequency in MHz, d_f is the vegetation (foliage) depth in m and x,y,z are parameters depending on the model selected. Table 1 presents the values chosen for x,y and z for every model studied.

	ITU-R	MED (d >= 14m)	COST 235 (out-of-leaf)	COST 235 (in-leaf)	FITU-R (out-of-leaf)	FITU-R (in-leaf)	Seville
x	0.2	1.330	26.6	15.600	0.37	0.39	0.37
y	0.3	0.284	-0.2	-0.009	0.18	0.39	0.30
z	0.6	0.588	0.5	0.260	0.59	0.25	0.38

Table 1: Parameters used for every model

We performed simulations of vegetation loss for each model above presented using the 28 GHz frequency band. The results are presented in figure 2.

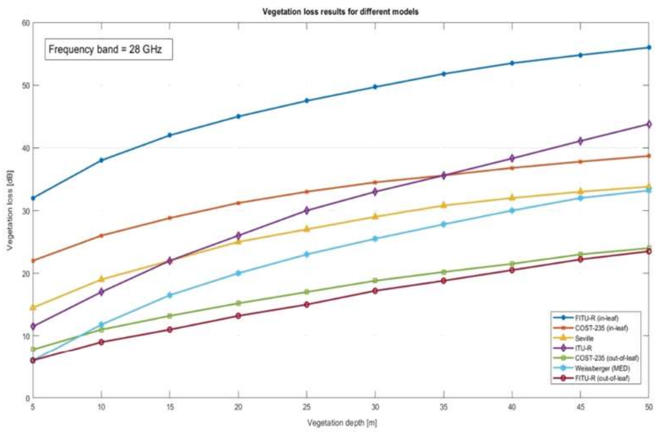

Figure 2: Vegetation loss simulation results.

The graph above demonstrates that the rise in vegetation loss is exactly proportional to the depth of the vegetation. The FITU-R (out-of-leaf) model has the lowest loss values at both 5 m and 50 m depth. Out-of-leaf models exhibit a smaller loss than their in-leaf counterparts. Since leaves play a major part in this type of loss, this behavior is natural. Greater loss occurs when leaves are present. The Seville model yields the best performance for vegetation loss. It has a value of around 31 dB at just 5 m depth, which is greater than the FITU-R (out-of-leaf) value of 22 dB at 50 m depth. Our models indicate that at a depth of 50 meters, the loss for FITU-R (out-of-leaf) is around 58 dB, which is the worst-case scenario.

ITU-R had the most increase in vegetation loss, from 5m to 50m. The loss at the initial measurement point, 5 m, is around 11 dB, but at a depth of 50 m, it is 45 dB, a substantially greater number of 34 dB. The other models are similar and the values for the vegetation loss are closer one to another.

In scenarios where indoor coverage from an outdoor 5G antenna have to be provided, it is required to assume also a certain penetration loss in the coverage calculations.

It is clear that the attenuation behavior of signals that penetrate walls depends on the frequency band of the signal as well as on the consistence of penetrated obstacles (building types and materials such as glass surface, concrete walls, room dividers, etc).

Following, we present a comparison of losses between penetration loss for soft materials and penetration loss for hard materials at different frequency bands.

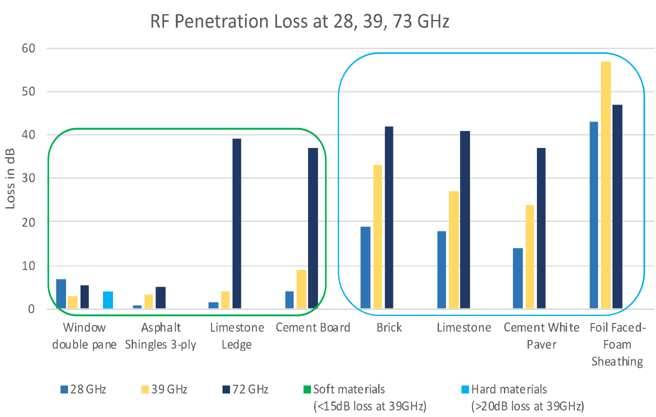

Figure 3: Penetration loss for soft and hard materials.

There were three frequency bands measured: 28 GHz, 39 GHz, and 73 GHz. As predicted, the penetration loss is substantially lower for soft materials than for hard ones. In the 39 GHz bandwidth, the loss increases exponentially as the hardness of the material increases. For foil faced-foam sheating, the penetration loss is over 60 dB at its maximum. Regarding the value of the loss, the materials are divided. Soft materials are those with a loss of less than 15 dB when considering 39 GHz, whereas hard materials (brick, concrete) are those with a loss of more than 20 dB.

For the assessment of the average penetration loss in our work, we utilized the generalized 3GPP TS 38.901 model (3), taking into consideration the fraction of window area included within the building's outside wall. In order to do so, initially we determined the loss of penetration for multi-pane glass, Infra Red Rejection (IRR) glass, wood and concrete at 3.5, 4.5, 6, 28, and 39 GHz. Table 2 provides the formulas used to compute the penetration loss of the materials.

Material	Penetration Loss [dB]
Standard multi-pane glass	$L_{glass} = 2 + 0.2f$
IRR glass	$L_{IRRglass} = 23 + 0.3f$
Concrete	$L_{concrete} = 5 + 4f$
Wood	$L_{wood} = 4.85 + 0.12f$

Table 2: Different materials parameters for penetration loss.

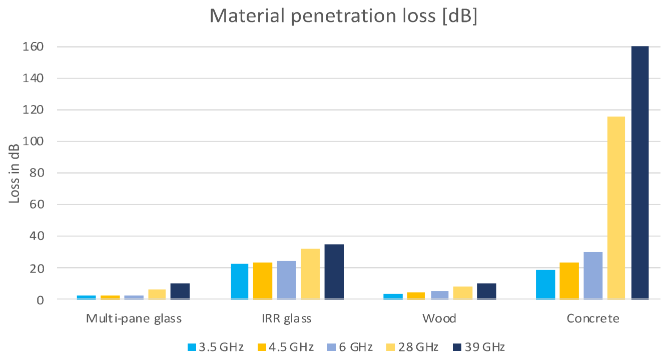

Figure 4: Material penetration loss.

Figure 4 depicts the values of the penetration loss for each of the given materials. Multi-pane glass and wood have low values for penetration loss in all investigated frequency bands, but what is truly fascinating is that in the lower frequency bands, IRR glass has a higher penetration loss than concrete. However, when the frequency rises, the concrete's loss increases dramatically. Therefore, for mmWave, it is extremely hard to penetrate concrete.

Following, we calculated the penetration loss for a building taking into consideration the glass percentage used for the walls. To calculate it we used Nokia's 5G Link Budget tool and the following equation:

$$PL_{tw} = 5 - 10 \cdot \log_{10}\left(A_{window} \cdot 10^{\frac{-L_{window}}{10}} + A_{wall} \cdot 10^{\frac{-L_{wall}}{10}}\right) \qquad (3)$$

where PL_{tw} is the path loss through external wall in dB, A_{window} is the percentage of the windows area within external building wall, A_{wall} is the percentage of the wall area within external building wall, L_{window} is the penetration loss of the windows and L_{wall} is the penetration loss of the wall. Figure 5 depicts the results after the simulation performed on a building, applying different percentages of glass on its walls, removing gradually the concrete.

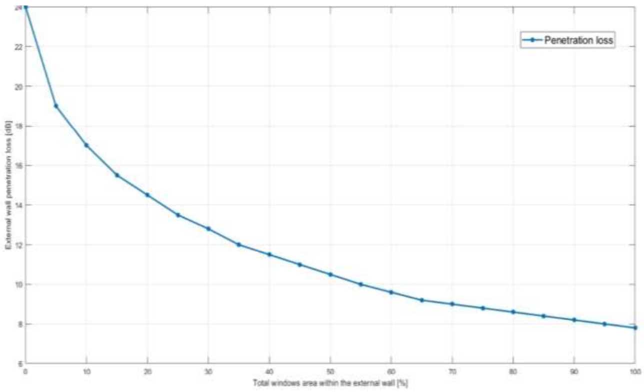

Figure 5: Penetration loss for different percentage of glass mounted in the external wall.

As the amount of glass replacing concrete on the exterior walls grows, the loss is continually reduced. This is expected because, as seen in figure 4, glass introduces a lower penetration loss than concrete.

IV. Conclusions

In this paper we analyzed the vegetation loss in scenarios where trees or other plants on the propagation way can be observed taking into account calculations performed with the Nokia's 5G Link Budget tool. Additionally, the penetration loss was calculated and explored for different scenarios and materials. Vegetation and penetration losses cannot be neglected when dealing with the mmWave spectrum. Our results assist when designing a network that uses high frequency bands and should be taken into consideration so that the performance of the system is as expected.

As future work, we will continue to investigate the penetration loss for normal window glass and glazed glass. In this way it can be determined which one is preferred to be used and also help for the development of future networks.

V. References

[1] F. Qamar, M. Hindia, K. Dimyati, K. A. Noordin, M. B. Majed, T. Rahman and I. Amiri, "Investigation of future 5G-IoT millimeter-wave network performance at 38 GHz for urban microcell outdoor environment," *MDPI Electronics Journal,* vol. 8, no. 5, p. 495, 2019.

[2] F. Qamar, M. H. S. Siddiqui, M. N. Hindia, K. Dimyati, T. A. Rahman and M. S. A. Talip, "Propagation Channel Measurement at 38 GHz for 5G mm-wave communication Network," *IEEE Student Conference on Research and Development (SCOReD),* pp. 1-6, 2018.

[3] H. Lin, H. Zhu, Y. Yang, G. Huang, K. Huang and Y. Chen, "Robust Channel Estimation for 5G mm Wave Massive MIMO Relay Communication Systems," *IEEE 21st International Conference on Communication Technology (ICCT),* pp. 289-294, 2021.

[4] H. Z. e. al., "28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city," *IEEE International Conference on Communications (ICC),* pp. 5163-5167, 2013.

[5] A. Seville, J. Richter, D. Ndzi, N. Savage, R. Caldeirinha, A. Shukla, M. Al-Nuaimi, K. Craig, E. Vilar and J. A. N. Rogers,

"A Generic Model of 1-60 GHz," *UK Radiocommunications Agency,* 2002.

[6] M. S. e. al, "Microwave vs. Millimeter-Wave Propagation Channels: Key Differences and Impact on 5G Cellular Systems," *IEEE Communications Magazine,* vol. 56, no. 12, pp. 14-20, 2018.

[7] H. Sun, H. Zhu, C. Ding, B. Jones and J. Guo, "Scattering Suppression in a 4G and 5G Base Station Antenna Array Using Spiral Chokes," *IEEE Antennas and Wireless Propagation Letters,* vol. 19, no. 10, pp. 1818-1822, 2020.

[8] D. Ogata, A. Sato, S. Kimura and H. Omote, "A Study on Vegetation Loss Model with Seasonal Characteristics," *14th European Conference on Antennas and Propagation (EuCAP),* 2020.

[9] R. Schulpen, L. A. Bronckers, A. Smolders and U. Johannsen, "5G Millimeter-Wave NLOS Coverage Using Specular Building Reflections," *14th European Conference on Antennas and Propagation (EuCAP),* 2020.

[10] R. Zhu, Y. E. Wang, Q. Xu, Y. Liu and Y. D. Li, "Millimeter-wave to microwave MIMO relays (M4R) for 5G building penetration communications," *IEEE Radio and Wireless Symposium (RWS),* pp. 206-208, 2018.

[11] Al Salameh, Mohammed. (2014). Lateral ITU-R foliage and maximum attenuation models combined with relevant propagation models for forest at the VHF and UHF bands. *International Journal of Networking and Communication.*

[12] Ozuomba, Simeon & Johnson, Enyenihi & Udoiwod, Emmanuel. (2018). Application of Weissberger Model for Characterizing the Propagation Loss in a Gliricidia sepium Arboretum. *Universal Journal of Communications and Network*. 6. 18-23.

[13] Cama-Pinto, Dora et al. "Path Loss Determination Using Linear and Cubic Regression Inside a Classic Tomato Greenhouse." *International journal of environmental research and public health* vol. 16,10 1744. 17 May. 2019

[14] H. M. Rahim, C. Y. Leow and T. A. Rahman, "Millimeter wave propagation through foliage: Comparison of models," *2015 IEEE 12th Malaysia International Conference on Communications (MICC), 2015*, pp. 236-240, doi: 10.1109/MICC.2015.7725440.