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Evaluation of Path-Loss Models for THz Propagation in Indoor Environments

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***Abstract*—In this paper, we evaluate the path-loss models that can be adopted for indoor communications in the TeraHertz (THz) frequency band. Three different models are investigated versus distance; namely, the ITU, the log-distance (LD), and the multi-wall COST 231 models. The latter exhibits much higher path-loss than the other two because it is able to account more accurately for the interior obstacles of indoor environments.**

***Index Terms*—TeraHertz, path-loss, log-distance (LD), ITU, multi-wall, COST 231.**

I. INTRODUCTION

Today, the need for higher data rates grows exponentially following Edholm's law [1]. To counter the demand for high bandwidth from a large number of users, we can either increase the spectral efficiency above 10 bits/s/Hz or the bandwidth above 20 GHz [2]. The first approach is relatively hard to achieve due to innumerable difficulties related to government regulations and standardization issues set by regulatory organizations. The second is more feasible by deploying THz frequencies since it is still an unregulated spectrum [3]. Actually, THz has been used for the last 25 years for imaging (e.g., remote sensing) and spectroscopy applications. However, it is one of the least tapped regions of the electromagnetic spectrum that holds a lot of potential for wireless communications [3], [4].

THz was first studied formally by Fleming in 1974. In [5], Michelson interferometer was used to record spectra in the THz region. The latter is widely used in industry for the measurement of small displacements and surface irregularities. This particular band has a frequency ranging between 0.1-10 THz [6], [7] and can fulfill the 10 Gbit/s requirement of 5G networks [8]. It is noted also that the THz band has some similar properties to the sub-millimeter wavelength values that fills wavelength between 0.1 and 1 mm (i.e., 300 GHz - 3 THz). Despite the attractive advantages of THz communications, some challenges need to be addressed. Indeed, THz communication systems suffer from high path-loss. Some solutions to counter key practical challenges were studied and one of the promising solutions suggests using graphene when designing the antenna elements [9]. Graphene has also its own practical challenges. The first is the high cost of extraction. The second is the significant performance loss stemming from harsh weather conditions. The authors in [10] developed for the first time resonant tunneling diodes (RTD) that use THz band as medium of communication between connected devices. The achievable range is 10 meters, which is a significant progress in the telecom domain. RTD has long been studied due to its ability to function at ultra-high-speed rates with low-power electronics and the fascinating property of negative differential resistance (NDR) [11].

Indoor propagation path-loss was widely investigated. In [12] a channel attenuation model is developed using the measurement data collected by the same team. The authors in [13] have studied the path-loss in the ISM bands of 33, 868 and 915 MHz. The work in [14] provides a comparative study of multiple empirical models for urban environments by considering the 868 MHz frequency band in long-range wide-area network (LoRaWAN). Therefore, current state of the art leaves a big gap in terms of studying the propagation path-loss for indoor communication technologies at THz band frequencies. To the best of our knowledge, the comparative study presented in this paper is relatively new and has not been tackled before for indoor propagation at THz frequencies.

The rest of the paper is organized as follows: In Section II, we provide an overview of THz communications. In Section III, we study the three path-loss models in the THz bands. In Section IV, we assess and compare the performance of these models. Finally, we draw out some concluding remarks in Section V.

II. THZ COMMUNICATIONS: STANDARDIZATION AND APPLICATIONS

As shown in Fig. 1, the THz band is positioned between the microwave and mid-infrared bands [15]. As stated in [16], it finds advantageous applications both in electronics and photonics. Moreover, THz is extremely beneficial to the telecommunication industry since it can carry much more bandwidth. It has also a good penetration property in opaque materials with high chemical selectivity and excellent use in imaging.

A. Applications

THz is widely used today in the detection of pharmaceutical medicines [17]. Recently, it has been used for temperature

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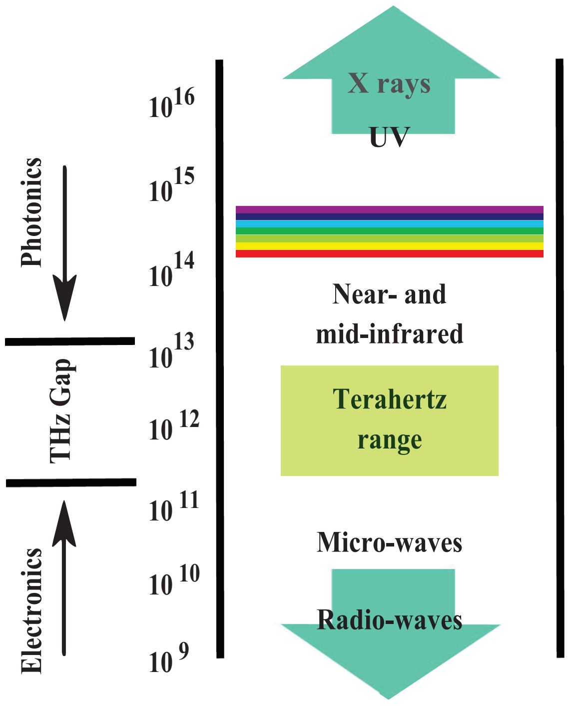

Fig. 1: THz positioning in the radio spectrum.

sensing applications [18]. It is being considered also for use in battlefield communications, particularly for short-range wideband communications, since it is sustainable in dry and smoky climates [16]. Another application of THz includes RADAR systems due to its excellent directionality and energy concentration features.

B. Standardization

IEEE has set a specific standard that is still under investigation by the IEEE 802.15.3d open discussion group. The latter focuses on high data rate transfers over PHY-layer THz bands [19]. Since its inception, this working group on THz has proposed eight channel bands that are multiples of 2.16 GHz, two signaling modes with seven modulation schemes (BPSK, 16-QAM, etc.) and three channel coding schemes [20].

III. PROPAGATION PATH-LOSS MODELS

In this section, we investigate the propagation path-loss models w.r.t. distance that are compatible with the THz band in the indoor environments.

A. Log-Distance (LD) Model

The LD model is commonly used for predicting the path-loss of a signal in an indoor scenario or a dense environment. For a source emitting at a wavelength λ, the path-loss is given by [21]:

$$L_{LD} = L_{FS}(\lambda, d_0) + e\ 10\log_{10}\left(\frac{d}{d_0}\right) + X, \tag{1}$$

where the distance, d, refers to the separation between the receiver from the transmitter in meters. The path-loss exponent (PLE) [22], denoted as e, depends on the propagation environment (e.g., $e = 2.01$ for THz [23]). L_{FS} is the free-space (FS) path-loss at a reference distance d_0 in meters which is given by:

$$L_{FS}(\lambda, d_0) = 20\log_{10}(4\pi d_0/\lambda). \tag{2}$$

X is a zero-mean Gaussian random variable of variance σ^2 that models large-scale fading such as log-normal shadowing [24].

B. ITU Model

This propagation model, defined by the International Telecommunication Union (ITU), has been developed to predict the median path-loss and it is based on diffraction theory. It is given in dB as follows [25]:

$$L_{ITU} = 20\ \log_{10} f_{\text{MHz}} + \eta\log_{10}(d) + P_{fl}\left(n\right) - 28, \tag{3}$$

where η is the power decay index (set to 19.5 as mentioned in [26] for THz) and f_{MHz} is the frequency in MHz. The parameter n is the number of floors separating the transmitter from the receiver while $P_{fl}\left(n\right)$ is the floor penetration loss. Note that $P_{fl}\left(n\right) = 0$ for $n = 1$.

C. Multi-Wall COST 231 Model

There are various versions of COST 231 such as COST 231-Walfisch-Ikegami for path-loss prediction that is suited for outdoor environments. Since we are studying the indoor propagation, we rather investigate the basic COST 231 path loss model [27] defined as:

$$L_{C231} = 32.4 + 20\log_{10} f_{\text{GHz}} + 20\log_{10}\left(S + d\right) + L_{indoor}, \tag{4}$$

where f_{GHz} is the frequency in GHz, S is the outdoor path (S is set zero in indoor environments), and L_{indoor} can be explicitly expressed as:

$$L_{indoor} = L_e + L_{ge} + max\left(\Gamma_1, \Gamma_2\right) \tag{5}$$

where L_e is the normal incidence on penetration in the first wall [28], L_{ge} is an approximation of the added loss due to an angle of incidence θ and is measured over an average of empirical values of incidence. The term $max\left(\Gamma_1, \Gamma_2\right)$ is an estimate of the loss within the building.

IV. SIMULATION RESULTS

In this section, we evaluate the above-mentioned models for better insight regarding THz frequencies. We use MATLAB 2019 cloud to perform the simulations below. Conducted experiments mainly focus on assessing the path-loss in the THz frequency range and comparing them with those measured with current radio access technologies such as LTE and WiFi bands. The considered environment is a single floor with a maximum distance of 15 meters between the transmitter and the receiver. In the following, we evaluate the path-loss for the three ITU, LD, and COST 231 models briefly introduced

TABLE I: Parameter values adopted by different path-loss models for various radio access technologies.

Model Type	Parameter	THz	LTE 2 GHz	WiFi 2.5 GHz	WiFi 5 GHz
LD	e	2.01	1.9	1.6	1.8
ITU	η	19.5	18	18	18
	P_{fl}	0	0	0	0
COST 231	L_e	3	3	3	3
	L_{ge}	6.1	6.1	6.1	6.1
	Γ_1	3	3	3	3
	Γ_2	0	0	0	0

in the previous section. These models require parameters that depend on the frequency band, as summarized in Table I.

We start by evaluating in Fig. 2 the ITU model path-loss versus the distance d between the transmitter and receiver at multiple frequency bands including THz, LTE (i.e., 2 GHz), and WiFi bands. The latter accounts for various frequency bands, the most popular being the 2.4 GHz and 5 GHz [29]. The latter are included in the IEEE standards 802.11a, 802.11b, 802.11g, and 802.11n. As expected, the path-loss increases with distance at all frequency bands. We also observe a significant increase in the path-loss at the THz frequency when compared with the remaining ones.

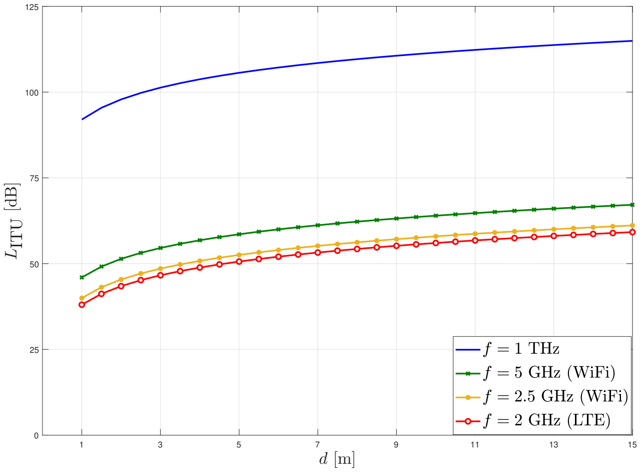

Fig. 2: ITU path-loss model vs. distance at different frequency bands.

In Figs. 3 and 4, we evaluate the LD and FS path-loss models versus the distance at the same frequency bands (i.e., THz, WiFi, and LTE). From Fig. 3, the LD path-loss model exhibits the same behavior as the ITU model. Path-loss values reported in the LTE band exceed those measured in the WiFi 2.5 GHz band at distances above 5 m. Such behavior stems from the fact that each band has its own power decay index, as defined in Table I. The FS model, however, does not account for any power decay index.

In Fig. 5, we reproduce the same path-loss curves for the multi-wall COST 231 model. Clearly, this model exhibits much higher path-loss values than the other two. The gap between them reflects the inclusion of the indoor component, L_{indoor}, that captures the additional attenuation factors stemming from propagation across walls and corridors.

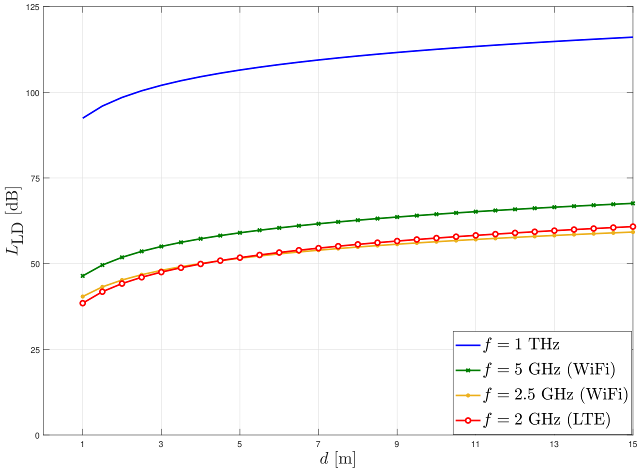

Fig. 3: LD path-loss model vs. distance at different frequency bands.

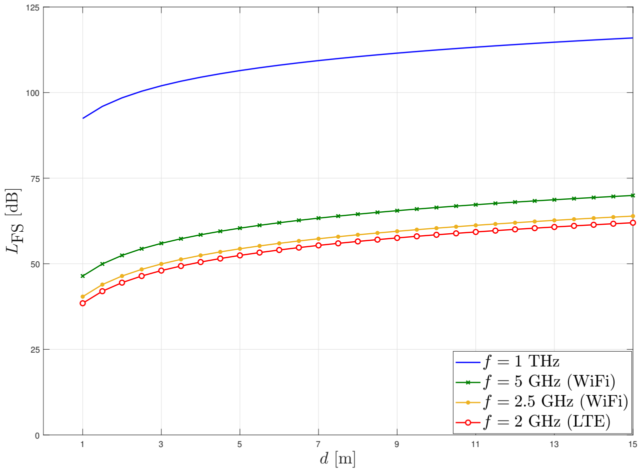

Fig. 4: FS path-loss model vs. distance at different frequency bands.

In Fig. 6, we evaluate all three path-loss models versus frequency in the THz band. We observe that both the ITU and LD models exhibit approximately the same performance. The FS model is actually coinciding with the LD model since values are evaluated at the reference distance $d_0 = 1$ m. Hence, the second term of the LD model in (1) becomes equal zero. Furthermore, the COST 231 model shows significantly larger path-loss values since it accounts for multi-wall attenuations.

In Fig. 7, we analyze the path-loss in a more complex indoor environment having multiple walls and corridors using the ray-tracing tool developed in [30]. The transmitter is placed in the middle of the main room. As a reference distance, we set its width to 5 m. We observe that the ITU, LD, and FS models exhibit the same omni-directional propagation. This is due to the fact that these models do not account for any obstacles

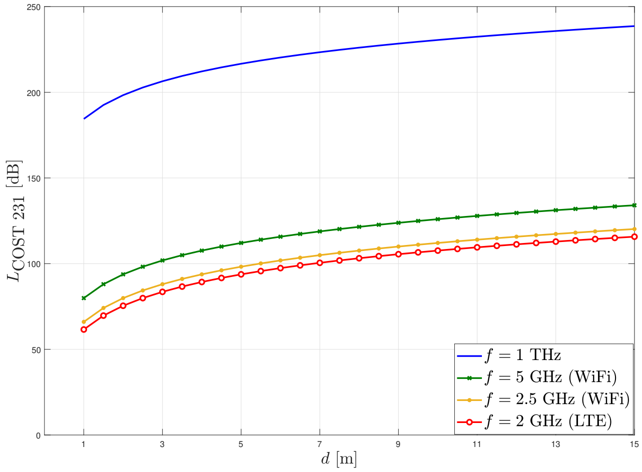

Fig. 5: COST 231 path-loss model vs. distance at different frequency bands.

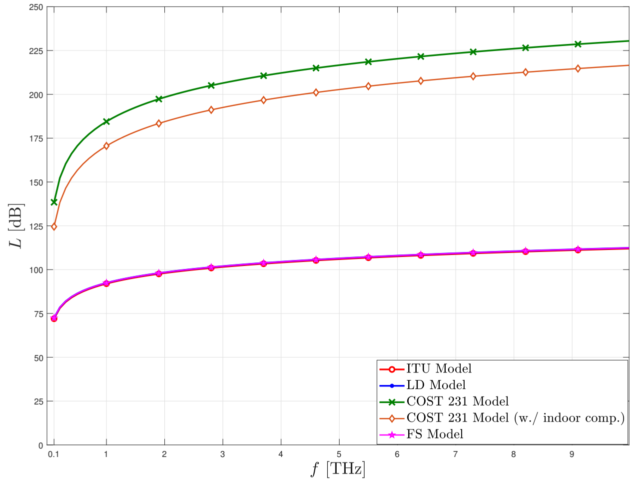

Fig. 6: ITU, LD, FS, and COST 231 path-loss models vs. frequnecy in the THz band at the reference distance $d_0 = 1$ m.

present in the indoor environment. On the other hand, the heat map for the COST 231 model exhibits a different pattern that clearly accounts for the type of indoor environment and its interior walls and obstacles.

V. CONCLUSION

In this paper, we proposed a comparative study of certain path-loss models that can be adopted for indoor communications in the TeraHertz (THz) frequency band. Three different models were investigated versus distance; namely, the ITU, the log-distance (LD), and the multi-wall COST 231 models. The latter exhibits much higher path-loss than the other two because it is able to account more accurately for the interior obstacles of indoor environments.

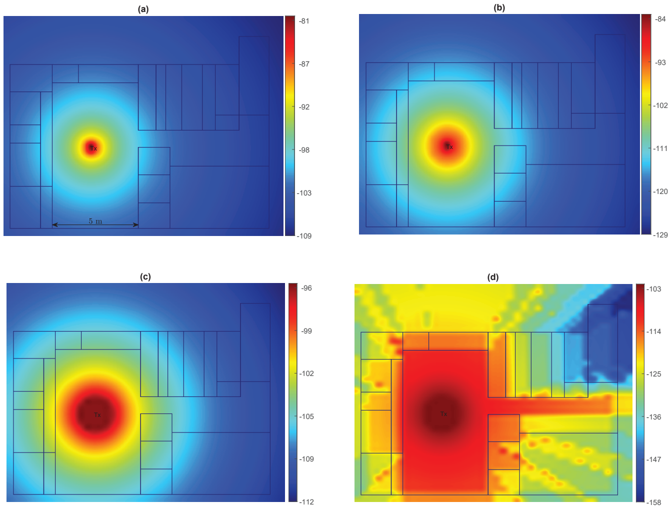

Fig. 7: Path-loss heatmap in a typical indoor environment for different propagation models: (a) ITU, (b) LD, (c) FS, and (d) COST 231.

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