Received 22 December 2023; accepted 10 January 2024. Date of publication 18 January 2024; date of current version 26 March 2024.
Digital Object Identifier 10.1109/OJAP.2024.3355817

Mm-Wave Building Penetration Losses: A Measurement-Based Critical Analysis

SILVI KODRA, MARINA BARBIROLI, ENRICO MARIA VITUCCI (Senior Member, IEEE), FRANCO FUSCHINI, AND VITTORIO DEGLI-ESPOSTI (Senior Member, IEEE)
Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi," CNIT, University of Bologna, 40126 Bologna, Italy
CORRESPONDING AUTHOR: S. KODRA (e-mail: silvi.kodra2@unibo.it)

This work was supported in part by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (Program "RESTART") under Grant PE00000001; in part by the Eu Project 6G-SHINE (6G Short Range Extreme Communication in Entities), Horizon Europe Programme under Grant 101095738; and in part by the Eu COST Action INTERACT (Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions) under Grant CA20120.

ABSTRACT The limited power-budget is known to be one of the main constraints in mm-wave radio links, especially when in-building applications are considered. In particular, outdoor-to-indoor and through-floor attenuation need to be analysed and carefully characterized at mm-waves in order to correctly approach both coverage and interference assessment issues. Surprisingly, only a few studies addressed the problem and no recommendation has been provided by standardization bodies so far for mm-wave through-floor attenuation in different building types. Therefore, a measurement campaign at 27 and 38 GHz was carried out to investigate the aforementioned issues. It is observed that in-building losses heavily depend on the building type, and that modern construction techniques make through-floor penetration almost impossible. This fact highlights the need for standard models for mm-wave through-floor propagation in different kinds of buildings.

INDEX TERMS Floor penetration loss, mm-wave frequencies, outdoor-to-indoor propagation.

I. INTRODUCTION

IN THE field of wireless communication, ensuring seamless indoor radio coverage, either from outdoor or indoor base stations or access points, is of paramount importance. Unfortunately, wall and floor penetration attenuation heavily hinder it, especially at mm-wave frequencies. Strong attenuation leads to a twofold outcome: it is undesirable when the primary goal is uninterrupted coverage, yet it can suppress interference, which is desirable in many applications. One key propagation mechanism in buildings is Outdoor to Indoor (O2I) propagation, especially in small-indoor residential and industrial environments, where the installation of dedicated micro-cells or repeaters is not cost-effective. In O2I propagation two different elements can be considered: Building Entry Loss (BEL) and Building Penetration Loss (BPL). As per ITU Recommendation [1], the difference between the mean signal level outside of the illuminated façade of the building and the mean signal level just inside the building, in the proximity of the same wall, is defined as BEL. BEL strongly depends on the wall materials, construction technique [2] and on the operating frequency. BPL, on the contrary, includes the BEL plus the attenuation due to propagation inside the building, therefore it includes extra loss due to internal walls and furniture.

The recent use of new frequency bands at higher frequencies for fifth- and sixth-generation cellular networks, will aggravate coverage-related problems since both isotropic path-loss and wall/floor insertion loss will become higher [3], [4]. At the same time, going towards very high frequencies determines a very high cost of RF components. Therefore, the spectrum below 6 GHz and at the low mm-wave bands at around 27 and 38 GHz still represents a good choice for near-future communication systems [5], [6]. Various measurement campaigns related to O2I propagation have been documented in the existing literature [3], [7], [8], [9], [10], [11]. Nonetheless, O2I propagation at mm-wave frequencies is still scarcely investigated in old southern-European buildings, that are characterized by thick walls and brick construction.

© 2024 The Authors. This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License.
For more information, see https://creativecommons.org/licenses/by-nc-nd/4.0/

Another critical propagation mechanism that has received insufficient attention at mm-wave frequencies is through-floor propagation which is essential for minimizing co-channel interference between adjacent floors. The knowledge gap in through-floor attenuation at mm-frequencies is reflected in the lack of standardized models for this case. The only complete characterization of through-floor propagation is limited to lower frequencies [12], [13]. In [14] authors characterize path loss between floors up to 37 GHz, although these measurements were not point-to-point, and no specific correlation between the type of floor and penetration loss was established. O2I and floor propagation heavily depend on the building's structural characteristics and the considered frequency. For this reason, it is essential to conduct multiple measurements with different kinds of buildings and different frequencies. The models proposed by standardization bodies such as ITU/3GPP [1], [15] seem to lack flexibility in accommodating this diversity. Hence, there is a necessity for more adaptable models specifically designed for mm-wave propagation.

The aim of this paper is to examine O2I propagation - in terms of BEL and BPL - in two distinct buildings as well as through-floor propagation at 27 and 38 GHz across five representative types of buildings, each characterized by different construction materials and techniques. Following preliminary work reported in [16], the same O2I measurement campaign has been repeated employing a fixed transmitter instead of a drone since potential ambiguity was found coming from the unreliable pointing of the illuminating antenna due to drone instability. Moreover, through-floor attenuation in different buildings in terms of both mean attenuation and short-term spatial fluctuations of attenuation over different floor spots has been investigated. Attenuation through 2 floors was also measured when the power-budget was sufficient for the purpose.

Based on the measurements outcome, simple, parametric formulations for both O2I and through-floor attenuation are proposed and tentative parameter values are provided for different building types, frequencies, and number of interposed floors. In particular, the proposed BPL formula is derived as an extension of a previously developed formula for indoor propagation [17]: thanks to the use of simple, physically relatable parameters, the formula is shown to yield good agreement with measurements in the considered scenarios.

In Section II, the measurement setup for both the O2I and through-floor attenuation measurements is described, while the parametric models for O2I and through-floor attenuation are presented in Section III. Measurement results are analyzed and discussed in Section IV, and proper parameters are derived for the through-floor attenuation model in different types of buildings. Furthermore the proposed through-floor model has been verified with a blind test in a different sixth building, with same construction characteristics as one of the representative buildings considered in this study. Finally, conclusions are drawn in Section V.

II. THE MEASUREMENT CAMPAIGN

The equipment used during the measurements consisted of a SAF signal generator [18] at the transmitter side and a SAF spectrum analyser [19] at the receiver side. A horn antenna was fed by the signal generator in both campaigns at the transmitter side. Meanwhile, at the receiver side a horn antenna was used to characterize the propagation through floors and an omnidirectional antenna was required for O2I measurements in order to mimic a typical user equipment antenna and to capture all multipath components which contribute to the overall value of the received power. The characteristics of the measurement setups utilized in the two aforementioned campaigns, are summarized in Table 1.

A. OUTDOOR-TO-INDOOR MEASUREMENT SETUP

O2I propagation is a complex propagation process that consists of propagation through the external illuminated wall of the building and additional propagation through inner walls. To identify the different contributions, here BEL has been considered as an indicator of the losses that the signal suffers from as it penetrates through the external illuminated wall only. On the other hand, BPL includes the BEL plus the attenuation experienced by the signal while propagating deeper into indoor premises, including indoor partition wall attenuation. In this study, measurements are conducted in a residential area for both 27 and 38 GHz. In order to understand how the O2I propagation is influenced by the type of buildings, a 19-th century residential building and a more modern office building are chosen as the measurement environments. The mobile terminal is placed on a trolley specifically designed for the measurement campaigns, moving it on both outdoor and indoor locations in order to estimate BEL and BPL. The transmitter is placed 30 m far from the illuminated façade of the building, in order for the façade to fall within the main radiation lobe of the transmitting horn antenna. Firstly, the outdoor measurements have been carried out by moving the receiving antenna close to the illuminated façade of the building, along the route indicated as O1O2 in Fig. 1.

Indoor measurements are then performed moving the receiver in different routes inside the building as shown by indoor dashed lines in Fig. 1. Measurements have been performed on the same route twice, forward and backward, to verify the repeatability of the measurements and increase the number of samples. The BPL is then computed as the received power difference between outdoor and indoor measurements: in this way some systematic errors cancel each other out. On the other hand, in order to estimate BEL, the receiver needs to be moved only on the indoor receivers located close to the external wall: routes I1, I2 and I8 as shown in Fig. 1(a) for the ground floor and routes I1, I2 in Fig. 1(c) for the first floor of the old residential building are considered; routes I1, I2 as shown in Fig. 1(b) and routes I1, I2, I3 in Fig. 1(d) for the ground floor and for the first floor of the modern office building respectively are considered. Being the measurement differential, the impact of the antenna

TABLE 1. Characteristics of the measurement set-up.

Parameter	Model	Features
O2I Campaign		
Transmitter	SAF Tehnika J0SSAG14 Signal Generator	Frequency: 26-40 GHz , for Indoor Tx power : 5 dBm, for Outdoor Tx power : -3 dBm
Receiver	SAF Tehnika J0SSAP14 Spectrum Analyzer	Frequency : 26-40 GHz , Sensitivity : -111 dBm
Amplifier	Eravant SBP-2734033020-KFK-S1	Gain at 27 GHz: 28 dBi , Gain at 38 GHz : 27 dBi
Horn antenna	SAF Tehnika J0AA2640HG03 (Height: 2m)	Frequency: 26-40 GHz, Half Power Beam-Width: 12.5°(E-plane), 15°(H-plane)
Omni antenna	Eravant SAO2734030345-KFS1	Frequency : 26-40 GHz , Gain: 3 dBi , Half Power Beam-Width: 45° (E-plane), omni (H-plane)
Through-floor propagation Campaign		
Transmitter	SAF Tehnika J0SSAG14 Signal Generator	Frequency: 26-40 GHz , Tx power : 0 dBm
Receiver	SAF Tehnika J0SSAP14 Spectrum Analyzer	Frequency : 26-40 GHz , Sensitivity : -111 dBm
Amplifier	Eravant SBP-2734033020-KFK-S1	Gain at 27 GHz: 26 dBi , Gain at 38 GHz : 25 dBi
Horn antennas	SAF Tehnika J0AA2640HG03 (Height: 2m)	Frequency:26-40 GHz, Gain : 21 dBi

gain is negligible for the scope of this study. Since the buildings under consideration are two-floor buildings, indoor measurements are repeated both on the ground floor and on the first floor of each building, taking into account the transmit antenna gain values in the direction of each floor. Measurements have also been compared with the 3GPP TR 138 901 model [15], which accounts for O2I propagation for frequencies up to 100 GHz.

B. THROUGH-FLOOR MEASUREMENT SETUP

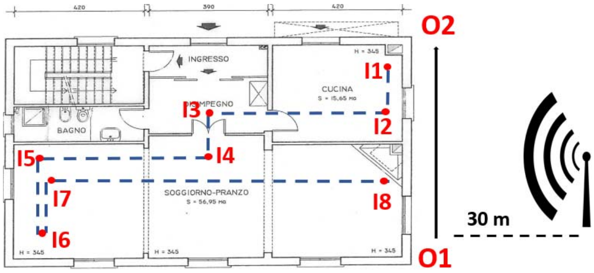
Measurements regarding the through-floor propagation were performed in five different typical buildings with structures of the floors as shown in Fig. 2 where the sixth measurement environment is only used to perform a blind-test on the proposed floor-attenuation model.

Both transmitter and receiver antennas have been installed on a tripod designed for measurement campaigns. Locations of the measured points were chosen in order for the transmitter and receiver to be vertically aligned in different floors as seen from Fig. 3b, obtaining in such way a point-to-point measurement of the floor attenuation. Having a wide set of propagation data is crucial for verifying the measurements reliability. As such, transmitter and receiver are moved to different positions inside the same room/hall where possible, or antennas are rotated by 120° due to a rotor installed in both tripods (see Fig. 3a). This way an accurate insight of the losses when signal passes through the floors is achieved. In order to filter out the random like time fluctuations, measurements were repeated 16 times in the same position and the median value of the received power was calculated at the receiver side. Through-floor loss (TFL) in dB is then calculated as the difference between the real measured received power (in dB) and the power one would gain in the free space as if the floor did not exist (in dB), as given by the equation:

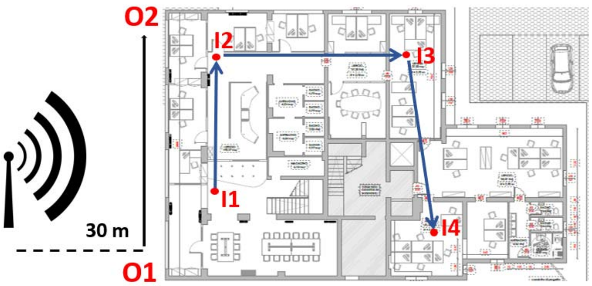
$$TFL\ (dB) = Pr_{measured} - Pr_{Friis} \tag{1}$$

Since a considerable number of measured points is obtained in each environment, the mean value of floor loss and its standard deviation are then calculated. These figures can be considered characteristic of each building type, which is related to its construction period, as described in the list below.

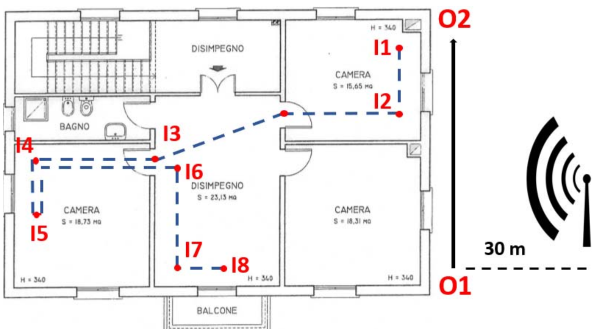
1) The first building is an old residential building (first case in Fig. 2), constructed in 17-th century, with floors made out of wooden structures. Specifically, the first floor of the building consists of only wooden structures while the second floor has been reinforced lately with a thin layer of concrete, making its structure different with respect to the first floor. Given the differences between the materials that are present in the two floors, floor propagation losses through the first and second floor separately was measured, as well as floor losses through two floors, since the relatively low loss of wooden floors allows to study this case as well. To this aim, since the building is a 3-floor structure, transmitter and receiver are placed in a wing of the building that allows all kind of measurements to be carried out on the same horizontal positions on different floors. Due to potential unevenness in the floor structure of old buildings, measurements of losses through the first floor are repeated 21 times by changing simultaneously with 10 cm step the locations of the transmitter and receiver along a predefined 2m long straight line. The same arrangement is followed for the measurement of losses through the second floor, with a step of 30cm instead of 10cm in this case. As for measurements of penetration loss through 2 floors, since furniture did not allow a



(a) Old residential building, ground floor



(b) Modern office building, ground floor

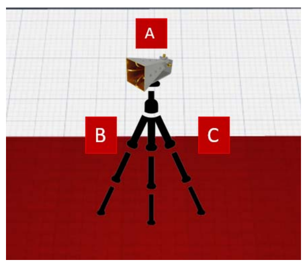


(c) Old residential building, first floor

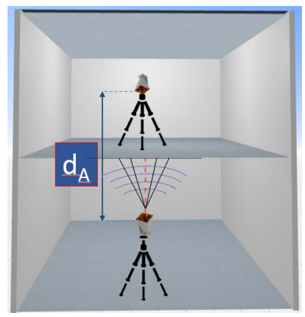
(d) Modern office building, first floor

FIGURE 1. Outdoor/Indoor measurement routes for O2I.

FIGURE 2. Different environments : Residential 17th century (first) University office of the 1930s (second) University hall of the 1930s (third), University office of the 1980s (fourth), University Hall 2010 (fifth), University building of the 1930s used for the blind-test (sixth).



(a) Rotating antennas 120°



(b) Antenna setup through 1 floor

FIGURE 3. Antenna setup for through-floor propagation.

full 2m scan, measurements on six different spots have been taken, rotating in the same way both antennas on positions A, B, C at an angular distance of 120° from each other, as shown in Fig. 3a. This process is repeated twice for each spot.

2) The second scenario is the University office area that was built around 1930 and has floors made of reinforced concrete (second case in Fig. 2). In this building, as in the previous old residential building, floor losses on both the first floor and the second floor separately have been investigated. By calculating the losses that each floor exhibits independently, insight on the homogeneity of the building as a whole is achieved, understanding whether measuring attenuation on a single floor alone is sufficient to represent the whole building. Measured points were taken along a straight line, for a total of 16 locations with 30 cm spacing between each-other, forward and backward on the same points for double check.

3) The third measurement environment is the hall of the University building (third case in Fig. 2) built around the year 1930, that has floors made of reinforced concrete. Here, apart from the floor thickness (28.5 cm), a 40 cm false ceiling is present, with several cables ducts and pipes. In this scenario, a 2m horizontal scan is performed, moving simultaneously both the transmitter and receiver with a 10 cm step on a straight line, as done in the aforementioned old residential building.

An attempt to measures losses through two floors was made also in this scenario, but it resulted that, as expected given the reinforced concrete structures, the received signal fell below noise floor.

4) In the fourth scenario, propagation through floors in more recent University office area built around 1980 is investigated. Metallic beams and metallic supportive structures are present in this type of construction. A 3m scan of the floor with a spacing of 30 cm between different measured points is performed, with some of the points falling directly on a metallic beam.
5) Lastly, the most modern environment is a University building built in 2010. Floor structure consists of a mixture of reinforced concrete, metal beams, double metal meshes and other metal supportive structures as shown in Fig. 8. Here, measurements are performed along a 2m line with a spacing of 10 cm, as before.

III. PROPOSED PROPAGATION MODELS

On the base of the trends observed in our measurements, we propose in this section simple parametric models for both O2I propagation and Through-Floor attenuation that can adapt to different type of buildings, including southern-European buildings.

A. OUTDOOR-TO-INDOOR PATH-LOSS MODEL

Since the 3GPP model [15] does not appear to be very suitable to describe BPL in the southern-European buildings considered in this study, especially when the indoor terminal is located well inside the building, an alternative parametric model is suggested in this section based on a modification of the indoor path-loss formula proposed in [17]. In this study, the formula is extended to account for BEL, as follows:

$$PL_{indoor} = PL_{Friis}(d_0) + BPL \tag{2}$$

where PL_{indoor} is the mean path loss (PL) of the outdoor-to-indoor link in dB, PL_{Friis} is free space path loss at the reference distance d_0 at the outer side of the building's wall - assuming free-space outdoor propagation - and BPL is the additional attenuation due to indoor penetration, which includes BEL and indoor propagation as described in [17]:

$$BPL\ (dB) = BEL + 10 * \alpha * log(d/d_0) + \beta * (d - d_0) \tag{3}$$

where, α is the path-loss exponent, β is a specific attenuation constant which accounts for excess attenuation due to the presence of walls or indoor clutter and d is the overall link distance. BEL can be extracted from measurement campaigns in different representative environments, see for example [3], [7], [8], [9], [10], [11]. Nevertheless, simple formula such as the one in [20] can be used to compute attenuation through a low-loss slab, if the effective material parameters (real and imaginary part of complex permittivity) of the wall are known at the considered frequencies. As stated in [17], if necessary, a proper fading description can be added to the foregoing formula, that only aims at providing mean O2I attenuation.

B. THROUGH-FLOOR ATTENUATION MODEL

Since no reference standard model is currently available, in this section we propose a simple parametric model for through-floor attenuation as a function of the number of interposed floors, expressed by (4). Let us denote with $\overline{L}$ and n_f, the average floor loss for a single floor and the number of interposed floors, respectively. In equation (4), the exponent β is a correction factor (with a value of 1 for propagation through only one floor), which takes into account the non-accumulative nature of losses when passing through multiple floors: β might have a value smaller than 1 in the case of through-multiple floor propagation. χ is a random variable with log-normal distribution that accounts for floor inhomogeneities with σ_L^2 being the building-specific standard deviation of the floor loss:

$$TFL\ (dB) = \overline{L} * n_f^{\beta} + \chi(0, \sigma_L^2) \tag{4}$$

Assuming the floor as a homogeneous slab of thickness th, floor loss can alternatively be expressed using a specific-attenuation value α_s [dB/cm], that depends on the construction material, as shown in (5):

$$\alpha_s\ (dB/cm) = \overline{L}/th \tag{5}$$

$\overline{L}$, σ_L^2 and α_s are derived through measurements in buildings of different construction year and type in the present work. Nonetheless, extensive measurements in other building types worldwide are needed to achieve a complete floor-loss table that could lead to the definition of a standard model. Regarding β we do not have enough data available in the present campaign and its determination is left for future work.

IV. RESULTS AND DISCUSSION

A. OUTDOOR-TO-INDOOR PROPAGATION

O2I measurements are carried out in two different environments and at two different frequencies: 27 GHz and 38 GHz. The first measurement environment is a brick-wall residential buildings with wooden window frames and wooden window blinds while the second one is an office building with walls made of metal panels, concrete and metal window frames.

Window glass is ordinary glass in both cases. Outdoor reference measurements are collected on O1-O2 routes, while indoor measurements are collected on multiple routes on different floors: see for example ground and first floor routes in Fig. 1. A comparison between measured O2I path loss and simulated O2I loss using the 3GPP TR 138 901 model [15] and the model proposed in Section III-A has been carried out and shown in Fig. 4 and Fig. 5. $\alpha = 2$ has been used in our proposed O2I path-loss model as suggested in [17] for small and mid-size buildings while β has been set equal to 1.6 for the old residential building and equal to 2.5 for the modern office building, for both the considered frequency bands, in agreement with clutter attenuation values found in other measurement campaigns [21], [22]. Since the new

TABLE 2. Mean BPL and BEL for the old residential building for measurements, 3GPP model [15] and the proposed O2I model.

Freq. [GHz]	Old residential building				
	Mean BPL [dB]			BEL [dB]	
	Measurement	*3GPP Model*	*Proposed O2I Model*	*Measurement-Proposed O2I model*	*3GPP Model*
27	28.1	23	29.13	22.4	21.5
38	30.4	25.7	31.74	25.6	22.6

TABLE 3. Mean BPL and BEL for the modern office building for measurements, 3GPP model [15] and the proposed O2I model.

Freq. [GHz]	Modern office building				
	Mean BPL [dB]			BEL [dB]	
	Measurement	*3GPP Model*	*Proposed O2I Model*	*Measurement-Proposed O2I model*	*3GPP Model*
27	24.1	16.3	26.79	20.3	13.1
38	34.5	18.5	36.42	31.6	15.4

model, differently from the 3GPP model, does not include predefined values for BEL, we used the measured BEL values here: this gives some advantage in terms of lower mean error to the proposed model. However, it will not influence the standard deviation of the error, which is the most relevant performance parameter. Figures 4 and 5 show the variations of BPL at ground floor vs. link distance as the receiver moves along indoor routes as described in Fig. 1. In the old residential building (Fig. 4), the receiver moves from I1 to I8 and then turns back on the same route from I8 to I1. In the modern office building, the receiver moves from I1 to I4 and then back from I4 to I1. It is clear that the 3GPP model underestimates losses in deep indoor locations (larger distances) while the proposed path-loss model better follows path-loss increase. This can be due to the denser construction of the considered buildings, that have thick partition walls made of bricks, better described by the β parameter of the new model, with respect to the lighted, open-space buildings considered when defining 3GPP model. The average values for the BPL and BEL at 27 and 38 GHz in the first environment are reported in Table 2 for all measurements, 3GPP model and the proposed O2I model. These mean values are computed across all routes on both floors to derive a representative figure for the whole building. It is evident that average BEL values are well reproduced by the 3GPP model in this environment, while average BPL is slightly underestimated. Also, for the considered building, the 3GPP model estimates a mild variation of attenuation with frequency, which is similar to measurements. For what concerns the modern office building (Fig. 5) it can be noticed from the graph that the 3GPP model predicts a lower BPL, especially for deep-indoor locations, with an underestimation of as much as 30 dB at about 10m from the outdoor wall, which is also reflected in Table 3. Moreover, while the attenuation predicted by the 3GPP model is still mildly dependent on frequency, measurements show a much higher attenuation at 38 GHz with respect to 27 GHz, due to the construction material of this building with metallic structures used in the reinforced concrete and window frames, differently from the residential house considered above.

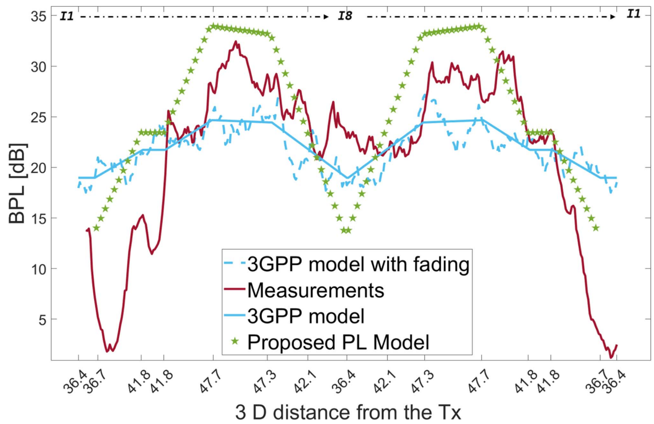


FIGURE 4. BPL for the old residential building at 27 GHz (ground floor).

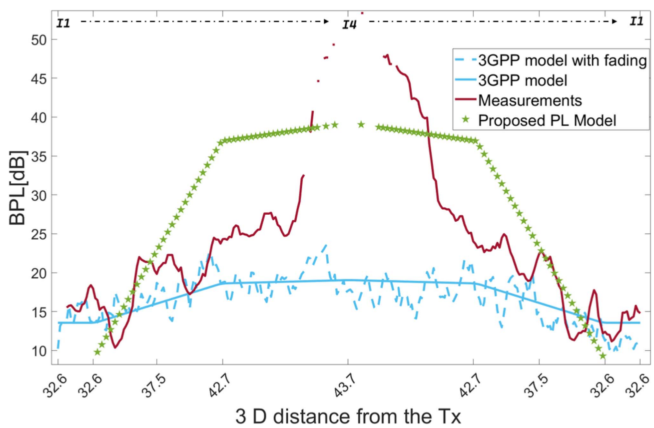


FIGURE 5. BPL for the modern office building at 27 GHz (ground floor).

Finally, in Table 4 the mean error and the standard deviation with respect to measured data calculated on both floors of each building are reported at 27 GHz for both the 3GPP model and the suggested O2I model. As can be noticed, the proposed O2I model shows smaller error standard deviation values with respect to the 3GPP model, highlighting the greater flexibility and accuracy of the proposed model, using standard literature values for parameter β.

TABLE 4. Mean error and standard deviation between measurements and 3GPP model and measurements and the proposed O2I model.

Frequency [GHz]	Model-measurement comparison							
	Old residential building				Modern office building			
	3GPP model		Proposed O2I model		3GPP model		Proposed O2I model	
	Mean error [dB]	Error Std. [dB]	Mean error [dB]	Error Std. [dB]	Mean error [dB]	Error Std. [dB]	Mean error [dB]	Error Std. [dB]
27	13.02	6.22	8.95	3.79	18.42	7.67	9.28	4.24

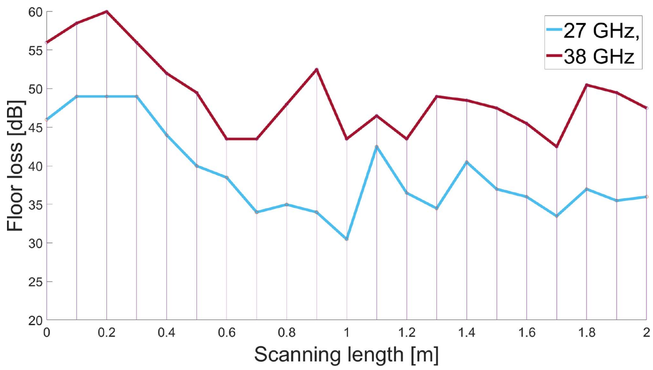


FIGURE 6. First floor 2m scan: Old residential building.

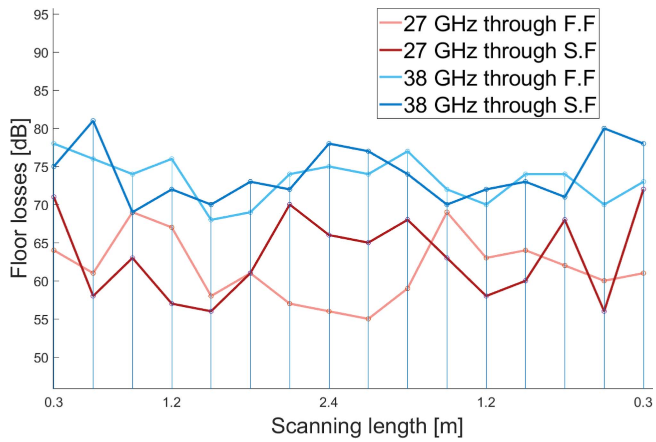


FIGURE 7. Office area building of the 1930s scan of First Floor (F.F) and Second floor (S.F).

B. THROUGH-FLOOR PROPAGATION

Propagation through floors is known to be problematic at mm-wave frequencies: here, floor-loss measurements at the 27 and 38 GHz in 5 different kinds of buildings are carried out, with the techniques explained in Section II. Due to the relatively small wavelength, through-floor attenuation depends on the particular microstructure of the floor layer along the Tx-Rx line. In the case of the 17th-century residential building, the initial 30 cm of the considered scanning length fell under a wooden beam, leading to higher penetration loss in this area as shown in Fig. 6. Furthermore, some variations can be noticed within the same frequency probably caused by irregularities or inconsistencies in floor composition. As expected, through-floor propagation suffers more at 38 GHz as compared to 27 GHz, with a mean attenuation of 49.53 dB and 39.18 dB, respectively, as shown in Table 5. Considering the attenuation through the second floor which has an added concrete layer with respect to the first floor, mean attenuation values increase significantly: 62.31 dB at 27 GHz and 80.4 dB at 38 GHz. For a better understanding of the variability of the attenuation through a single floor and thus the need for an evaluation of the mean loss value to be representative of the through floor attenuation, Fig. 6 and Fig. 7 show the floor scan of both the first and the second floor measurements for the office area of years ’30. In Fig. 7, a 2.4 meter scan of the first floor (noted as FF) and second floor (noted as SF) independently is shown while going and coming back. It can be noticed that there is approximately 5 dB of difference in the mean loss between the two floors. Moreover, in both the residential building of 17-th century and the office area of the 1930s, through-floor losses are strongly dependent on the operating frequency. Average losses as well as standard deviation and specific attenuation [dB/cm] are shown in Table 5 for all the buildings under consideration. It can be noticed that the old 17-th century residential building, having floors made of wooden structures, exhibits lower through-floor losses with respect to the newer University buildings. When comparing University buildings of the 1930s and 1980s it can be noticed that through-floor losses are lower for the building of the 1930s, for all the floors considered. However, in the University building of the 1930s, through-floor attenuation depends on the specific part of the building area under consideration, with the hall area having the highest attenuation. The most modern building, dated 2010, with floors equipped with multiple double metallic nets and beams as indicated in Fig. 8, completely blocks the signal penetration even through only one floor.

Such a structure becomes of particular interest when interference management is the primary objective. Meanwhile, propagation through two floors is possible in the 17-th century and in some points of the hall of years ’30 building, while the received power drops below the receiver sensitivity in modern buildings. Another important observation is that the standard deviation seems to be lower at 38 GHz with respect to 27 GHz in almost all cases. This behaviour is quite peculiar and deserves further investigation. However, the observed general trend is that the more modern the construction technique, the more difficult

TABLE 5. Summary of penetration losses through one floor.

Building type	27 GHz			th	38 GHz		
	$\overline{L}$ [dB]	σ_L [dB]	α_s [dB/cm]	[cm]	$\overline{L}$ [dB]	σ_L [dB]	α_s [dB/cm]
Residential 17-th century (through 1st F)	39.18	5.66	1.78	22	49.53	5.33	2.25
Residential 17-th century (through 2nd F)	62.31	7.92	2.49	24	80.4	4.1	3.22
Hall University building 1930s	77.67	6.93	2.73	28.5	89.88	6.26	3.15
Office area University building 1930s (through 1st F)	61.62	4.26	2.1	30	73.36	2.9	2.45
Office area University building 1930s (through 2nd F)	56.68	8.56	1.89	30	67.18	7.95	2.24
Office area University building 1980s	88.04	5.12	2.52	35	93.95	3.81	2.68
University building 2010	below noise floor			37	below noise floor		

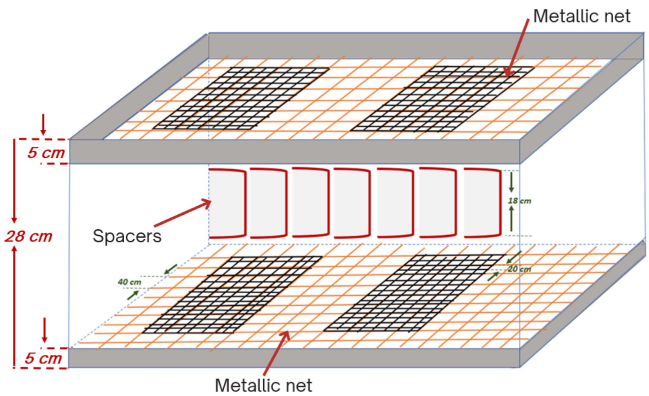


FIGURE 8. University 2010 : Floor structure.

it is for mm-wave signals to penetrate through floors. Lastly, a blind-test was performed on a new environment (see last picture of Fig. 2) that is similar to the Office area of the 1930s University building. By applying the corresponding specific attenuation coefficient proposed in Table 5 and considering the floor thickness of 35cm, the new measurement environment shows good agreement between mean attenuation predicted by our through-floor attenuation model ($\overline{L}_{model}$ = 66.1 [dB] at 27 GHz and $\overline{L}_{model}$ = 78.4 [dB] at 38 GHz) and the measured values ($\overline{L}_{meas}$ = 62.3 [dB] at 27 GHz and $\overline{L}_{meas}$ = 73.6 [dB] at 38 GHz), confirming the validity of the proposed model.

This study highlights the need for standard statistical models that can account for through-floor propagation at mm-wave frequencies in different types of buildings of different regions of the world. The proposed Table 5 can be further extended by including additional different types of buildings and frequencies carried out with further extensive measurement campaigns. Additional investigations will include the study of the variability range of the considered parameters and, in case, the determination of a general trend.

V. CONCLUSION

O2I and through-floor attenuation are two important mechanisms that become of crucial importance with the recent use of mm-wave frequencies, especially if the focus is on ensuring seamless indoor coverage and interference management. In general, O2I and floor propagation heavily depend on the structural features of buildings and on frequency. In this view, to ensure accurate path loss predictions, a large-scale characterization of the different building types is essential. Furthermore, O2I models proposed by the standardization bodies (ITU/3GPP) seem hardly adaptable to this diversity, while no standard model is currently available for through-floor propagation. To this aim this study conducts a critical analysis of O2I and through-floor propagation based on multiple measurement campaigns. Comparing O2I measurements with the 3GPP TR 138 901 model, it is observed that the model predicts fairly well the BEL but progressively underestimates BPL as the mobile terminal moves inside the buildings, due to the dense structure of the south-European buildings considered in this study. Moreover, it is highlighted that the frequency dependence of both BEL and BPL is strictly related to the type, thus construction materials, of buildings, with the brick walls of the residential building being weakly frequency dependent, and reinforced concrete being strongly frequency dependent, as for the office building. Overall, this dependence is not taken into account by the 3GPP model, thus there is a requirement for additional measurement campaigns that encompass a wide range of building types, including those found in southern Europe and that can extend the 3GPP model. A simple parametric O2I model based on the formula in [17] is proposed in this work. Results show that the proposed O2I model is able to capture the BPL variations and is more flexible than the 3GPP model.

As for through-floor propagation, having investigated five different buildings, it can be concluded that penetration becomes increasingly difficult with modern and highly insulating construction techniques. Propagation through two floors seems possible only in old buildings with wooden floors. Finally, a first-attempt, simple model formulation for though-floor propagation as a function of the type of building is proposed in this work.

REFERENCES

[1] *Effects of Building Materials and Structures on Radiowave Propagation Above About 100 MHz*, ITU-Rec. pp. 2040–2042, Int. Telecommun. Union, Geneva, Switzerland, Sep. 2021.

[2] A. A. Ayeni, A. A. Yusuf, and S. O. Onidare, "Correlation between the electromagnetic properties of building materials and wireless signal penetration loss," *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 12040–12048, Dec. 2022.

[3] Y. C. Lee et al., "Measurements of window penetration loss and building entry loss from 3.5 to 24 GHz," in *Proc. 13th Eur. Conf. Antennas Propagat. (EuCAP)*, 2019, pp. 1–4.

[4] S. Y. Jun et al., "Penetration loss at 60 GHz for indoor-to-indoor and outdoor-to-indoor mobile scenarios," in *Proc. 14th Eur. Conf. Antennas Propagat. (EuCAP)*, 2020, pp. 1–5.

[5] M. Mohsen and D. W. Matolak, "31 GHz path loss measurement and modeling for indoor/outdoor environments," in *Proc. Wireless Telecommun. Symp. (WTS)*, 2018, pp. 1–8.

[6] Z. Zhong, J. Zhao, and C. Li, "Outdoor-to-indoor channel measurement and coverage analysis for 5G typical spectrums," *Int. J. Antennas Propagat.*, vol. 2019, 2019, Art. no. 3981678. [Online]. Available: https://doi.org/10.1155/2019/3981678

[7] J. Du, D. Chizhik, R. Feick, G. Castro, M. Rodríguez, and R. A. Valenzuela, "Suburban residential building penetration loss at 28 GHz for fixed wireless access," *IEEE Wireless Commun. Lett.*, vol. 7, no. 6, pp. 890–893, Dec. 2018.

[8] J. L. Towers, S. Salous, X. Raimundo, and A. Cheema, "Building entry loss for traditional and thermally efficient houses between 0.4 and 73 GHz," in *Proc. 12th Eur. Conf. Antennas Propagat. (EuCAP 2018)*, 2018, pp. 1–4.

[9] M. Khatun, C. Guo, D. Matolak, and H. Mehrpouyan, "Indoor and outdoor penetration loss measurements at 73 and 81 GHz," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2019, pp. 1–5.

[10] W. Yang, J. Huang, J. Zhang, Y. Gao, S. Salous, and J. Zhang, "Measurements of reflection and penetration loss in indoor environments in the 39-GHz band," in *Proc. 15th Eur. Conf. Antennas Propagat. (EuCAP)*, 2021, pp. 1–5.

[11] S. Salous, B. M. Villacieros, and J. Bishop, "Building entry loss and clutter loss at 26 GHz," in *Proc. 14th Eur. Conf. Antennas Propagat. (EuCAP)*, 2020, pp. 1–4.

[12] S. M. Yee Aung and M. M. Maw, "Analysis of indoor channel propagation characteristics in multifloored building at 2.4 GHz," in *Proc. 21st Int. Comput. Sci. Eng. Conf. (ICSEC)*, 2017, pp. 1–5.

[13] A. C. M. Austin, M. J. Neve, and G. B. Rowe, "Modelling inter-floor radio-wave propagation in office buildings," in *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, 2008, pp. 1–4.

[14] M. Sasaki et al., "Path loss characteristics between different floors from 0.8 to 37 GHz in indoor office environments," in *Proc. Int. Symp. Antennas Propagat. (ISAP)*, 2016, pp. 66–67.

[15] "5G; study on channel model for frequencies from 0.5 to 100 GHz; (Release 16), version 16.1.0," 3GPP, Sophia, Antipolis, France, Rep. TR 138-901, 2020.

[16] F. Fuschini, M. Barbiroli, E. Vitucci, and V. Degli-Esposti, "Multiband outdoor-to-indoor propagation measurements using a drone," in *Proc. 16th Eur. Conf. Antennas Propagat. (EuCAP)*, 2022, pp. 1–4.

[17] V. Degli-Esposti, G. Falciasecca, F. Fuschini, and E. M. Vitucci, "A meaningful indoor path-loss formula," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 872–875, 2013.

[18] "SAF Spectrum Compact." Accessed: Jan. 27, 2024. [Online]. Available: https://spectrumcompact.com/

[19] "SAF Spectrum Compact:Spectrum analyzer." Accessed: Jan. 27, 2024. [Online]. Available: https://www.saftehnika.com/en/ebandspectrumcompact

[20] L. Possenti et al., "Improved fabry-Pérot electromagnetic material characterization: Application and results," *Radio Sci.*, vol. 55, no. 11, pp. 1–15, Nov. 2020.

[21] K. Du, O. Ozdemir, F. Erden, and I. Guvenc, "Sub-Terahertz and mmWave penetration loss measurements for indoor environments," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, 2021, pp. 1–6.

[22] N. Hosseini et al., "Attenuation of several common building materials: Millimeter-wave frequency bands 28, 73, and 91 GHz," *IEEE Antennas Propag. Mag.*, vol. 63, no. 6, pp. 40–50, Dec. 2021.

SILVI KODRA received the first M.Sc. degree in telecommunications engineering from the University of Bologna, and the second M.Sc. degree in electronics and communication engineering from Tongji University, Shanghai. She is currently pursuing the Ph.D. degree in telecommunications engineering with the University of Bologna. Under a grant from EurAAP, she spent one month of her research activity at Durham University, U.K., working on THz channel measurements. Her activity is focused on the research topic in reconfigurable intelligent surfaces, channel characterization for mm-wave and sub-THz frequencies, and propagation losses in indoor environments. She participates regularly in COST INTERACT.

MARINA BARBIROLI received the Laurea degree in electronic engineering and the Ph.D. degree in computer science and electronic engineering from the University of Bologna in 1995 and 2000, respectively, where she is currently an Associate Professor with the Department of Electrical, Electronic and Information Engineering "G. Marconi." Her research interests are on propagation models for mobile communications systems, with focus on wideband channel modeling for 5G systems and beyond. Research activities includes investigation of planning strategies for mobile systems, broadcast systems and broadband wireless access systems, analysis of exposure levels generates by all wireless systems and for increasing spectrum efficiency. The research activity includes the participation to European research and cooperation programs (COST 259, COST 273 COST2100, COST IC1004, COST IRACON, and COST INTERACT) and in the European Networks of Excellence FP6-NEWCOM and FP7-NEWCOM++.

ENRICO MARIA VITUCCI (Senior Member, IEEE) is currently an Associate Professor of Applied Electromagnetics, Antennas, and Propagation with the Department of Electrical, Electronic and Information Engineering "G. Marconi", University of Bologna. Formerly, he has been a Research Associate with the Center for Industrial Research on ICT, University of Bologna. In 2015, he was a Visiting Researcher with Polaris Wireless, Inc., Mountain View, CA, USA. He is the Chair of the Cesena-Forli Unit, Inter-Department Center for Industrial Research on ICT, University of Bologna. He is the author or a coauthor of about 100 technical articles on international journals and conferences, and co-inventor of five international patents. He participated to several European research and cooperation programs (COST 2100, COST IC1004, COST IRACON, COST INTERACT) and in the European Networks of Excellence NEWCOM and NEWCOM++. His research interests are in deterministic and wireless propagation models for 5G and beyond. He is a member of the Editorial Board of the Journal *Wireless Communications and Mobile Computing*.

FRANCO FUSCHINI received the M.Sc. degree in telecommunication engineering and the Ph.D. degree in electronics and computer science from the University of Bologna in 1999 and 2003, respectively, where he is currently an Associate Professor with the Department of Electrical, Electronic and Information Engineering "G. Marconi," University of Bologna. He is the author or coauthor of more than 40 journal papers on radio propagation and wireless system design. His main research interests are in the area of radio systems design and radio propagation channel theoretical modeling and experimental investigation. In April 1999, he got the "Marconi Foundation Young Scientist Prize" in the context of the XXV Marconi International Fellowship Award.

VITTORIO DEGLI-ESPOSTI (Senior Member, IEEE) is an Associate Professor with the "Dipartimento di Ingegneria Elettrica, Elettronica e dell'Informazione" (DEI), Alma Mater Studiorum, University of Bologna. From January 2015 to December 2016, he was the Director of Research with Polaris Wireless Inc., Mountain View, CA, USA. He was an Adjunct Professor with the Helsinki University of Technology (currently, Aalto University) and Tongji University, Shanghai, in 2006 and 2013, respectively. In 1998, he was a Postdoctoral Researcher with Polytechnic University, Brooklyn, NY, USA (currently, NYU Polytechnic) in the group led by Professor H. L. Bertoni. He is the author or coauthor of over 140 peer-reviewed scientific papers and a co-inventor of seven international patents in the fields of applied electromagnetics, radio propagation, and wireless systems. He is an Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY and an Associate Editor of the *Radio Science* and IEEE ACCESS. He is the Elected Chair of the Propagation Working Group of the European Association on Antennas and Propagation and the Working Group WG1 "Radio Channels" of the EU COST Action "Interact." He has been the Vice-Chair of the European Conference on Antennas and Propagation, editions 2010 and 2011, short-Courses and Workshops Chair of the 2015 edition, and an Invited Speaker at EuCAP 2014 and ISAP 2020.

Open Access funding provided by "Alma Mater Studiorum - Università di Bologna" within the CRUI CARE Agreement