Path Loss Validation for Urban Micro Cell Scenarios at 3.5 GHz Compared to 1.9 GHz

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***Abstract*—The 3.5 GHz band is a strong candidate for future urban micro cell deployment with base station antennas located below rooftop. Compared to other frequency bands, propagation in the 3.5 GHz band is relatively unexplored for the micro cell deployment. This paper presents a measurement-based analysis of outdoor and outdoor-to-indoor propagation at 3.5 GHz in comparison to the more well-known frequency of 1.9 GHz. A simple two-slope line-of-sight/non-line-of-sight outdoor path loss model is proposed and compared to different existing path loss models. The outdoor path loss is found to be approximately 5 dB higher for 3.5 GHz compared to 1.9 GHz. The outdoor-to-indoor propagation is investigated for two office buildings and different street shops. For the different presented scenarios, penetration loss increases with frequency and is found to be up to 5 dB higher for 3.5 GHz compared with 1.9 GHz. Although some existing models predict the observations with good accuracy, we propose a model based on line-of-sight probability that is simpler and easier to apply.**

I. Introduction

Micro cells are low power base stations intended to cover small areas up to a few hundred meters, where macro cells do not provide enough network coverage, or crowded areas where additional network capacity is needed. They are expected to play an important role in future mobile broadband networks such as Long Term Evolution (LTE) or LTE-Advanced. Moreover, the lack of spectrum available in the lower frequency bands (e.g. 800 MHz or 2 GHz) generates a huge interest in deploying small cells at higher frequency bands. The 3.5 GHz Time-Division LTE (TD-LTE) band is considered as a good spectrum candidate [1, 2], because it allows up to 200 MHz of bandwith with carrier-aggregation techniques, and many countries have this spectrum available.

Outdoor micro cell propagation has been covered in the literature for different frequency bands. The propagation at 900 MHz and 11 GHz for rural and urban line-of-sight (LOS) scenarios was studied in [3]. The attenuation was found to follow an inverse second power law before a breakpoint, changing to the fourth beyond that point. Similarly, [4] reported the same behavior for 800 MHz LOS micro cells in a dense-urban scenario. In [5], the authors found power decay factors close to free space path loss for both narrow and wide streets in urban scenarios for 1.8 GHz, and concluded that the changes in antenna height do not have significant effects on the path loss characteristics for below rooftop mounted antennas.

However, the path loss for the specific micro cell deployment in the 3.5 GHz band has not received much attention yet. Previous propagation studies reported in the literature for this frequency band have primarily focused on the deployment of Fixed Wireless Access (FWA) technologies such as Worldwide Interoperability for Microwave Access (WiMAX) in urban scenarios [6–9] and rural scenarios [10, 11]. These studies are performed on outdoor macro cells for a measurement distance range from a hundred meters to a few kilometers, with the base station antenna placed over the rooftop and the receive antenna at street level.

In general, when addressing indoor coverage, authors do not agree on the frequency dependence of the penetration loss. Most of the existing in-building radio propagation studies that are reported in literature are referred to the macro cell case. In [12] both building penetration loss and in-building attenuation are for the frequency range from 800 MHz to 8 GHz. The measurement results showed a constant penetration loss around 9.5 dB and an indoor attenuation based on the penetration distance of 0.6 dB/m, while [13] reports an average penetration loss of 17 dB in the frequency range from 900 MHz to 2.3 GHz. On the other hand, [14] found that penetration loss increases at the higher cellular frequencies (above 3 GHz). Generally, the authors remark the difficulty of estimating the penetration loss in the macro cell case due to the different illumination conditions and propagation mechanisms. For micro cells, the often cited Berg model [15] suggests a small variation of the penetration loss from 900 MHz to 1800 MHz, while [16] reported increasing penetration loss with frequency.

This paper complements the previous work by specifically addressing the urban micro cell scenario (urban pedestrian areas and office buildings, where micro cells are deployed at lamppost level below the rooftop), by focusing on the 3.5 GHz band in comparison with the more well known 1.9 GHz band. The propagation is investigated from different measurements for outdoor and outdoor-to-indoor conditions with the aim of developing models which are useful for standardization work and rudimentary planning purposes.

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The outdoor path loss is categorized into LOS and non-line-of-sight (NLOS) conditions, and compared to existing micro cell path loss models such as the 3GPP Low Power Node (3GPP-LPN) [17], ITU-R [18] and the WINNERII-B1 [19]. The 3GPP-LPN has been calculated for a fixed frequency of 2 GHz, and defined as a simple function of distance between the base station and the user equipment. On the other hand, the ITU-R and the WINNERII-B1 are applied for the frequency range of 2 GHz to 16 GHz and 2 GHz to 5 GHz, respectively. These models are not always easy to apply from a radio planning perspective. They consider different distances along streets which makes it necessary to track them and the different corners for all the micro cells present in the scenario. For this reason, a dual-slope LOS/NLOS outdoor path loss model is proposed in this paper, where the transition between the two conditions is defined by a LOS probability function estimated from the samples collected in the measurement campaign. For reference, the path loss is compared to well-known path loss models like Hata [20] and COST-Walfisch-Ikegami (COST-WI) [21] even though these models are not intended for micro cells, short range and frequencies above 2 GHz.

The outdoor-to-indoor propagation is investigated based on the measurements performed in two office buildings and various shops directly illuminated in LOS conditions. For the two different office buildings, the penetration loss is computed at three different levels of indoor penetration, while a simple outdoor-to-indoor transition is investigated for the shops.

The rest of the paper is organized as follows: Section II describes the measurement campaign, Section III presents the results and the path loss analysis at the two frequencies, and finally, Section IV concludes the paper.

II. Measurement Campaign

A. Measurement Setup

A simplified micro cell deployment was used for the measurement campaign. With the aim of identifying the path loss difference between 1.9 GHz and 3.5 GHz, two different continuous wave (CW) signals were generated and combined for transmission. The transmitter (TX) antenna was attached to a 7 m high wood mast by using a lamppost-like setup on top of a van containing all the transmitter equipment (Fig. 1). At the receiver (RX) side, two antennas were mounted on a trolley at 1.65 m height, with a separation of 0.5 m between them. The antennas used were H+S SWA-0859/360/4/10/V for both TX and RX sides. The signals from the two RX antennas at the two particular frequencies were independently recorded by a R&S TSMW radio network analyzer, which allows simultaneous radio frequency power scan measurements in its 2 front-ends. By using this setup, a direct comparison of the signal propagation at the two frequencies was possible. The scanner sensitivity is -130 dBm for a sampling rate of 1.6 samples/s. All the measurements were performed at slow walking speed (about 3 km/h).

Fig. 1: Transmitter and receiver setup.

B. Calibration

The main objective in this paper is the study and validation of path loss (PL), which is calculated as follows:

$$PL[\text{dB}] = P_{TX} - P_{RX} + G_{TX} + G_{RX} \quad (1)$$

where P_{TX} is the transmitted power in dBm measured at the TX antenna input port, P_{RX} is the received power in dBm calculated from the combination of the values measured at both RX antenna output ports, and $G_{TX} = G_{RX} = G_{meas}$ are the calibrated values of antenna gain in dBi. A summary of these values is presented in Table I.

TABLE I: Summary of the calibrated parameters.

	$\mathbf{P_{TX}}$	$\mathbf{G_{meas}}$	$\mathbf{G_{max}}$
1.9 GHz	14.9 dBm	0.81 dBi	6.24 dBi
3.5 GHz	13.1 dBm	1.71 dBi	6.39 dBi

The same antenna is used to transmit and receive both frequencies simultaneously. This fact allows a direct comparison of the propagation at the two frequencies, subject to the uncertainty in the antenna patterns. The theoretical radiation pattern for the antenna at 1.9 GHz and 3.5 GHz is shown in Fig. 2. As it can be seen, the antenna can be considered omnidirectional in the horizontal plane (azimuth). According to the theoretical pattern, the maximum deviation of the horizontal pattern around the mean value is 3 dB for 1.9 GHz and 4 dB for 3.5 GHz. The elevation pattern is also considered since it represents a big impact on the measurements, especially in LOS conditions. In the measurement region, the maximum elevation pattern deviation is 4 dB for 1.9 GHz and 5 dB for the 3.5 GHz, according to the theoretical pattern. In order to compensate for this deviation, the RX antennas are located upside-down with respect to the TX antenna, so the effective elevation region is similar for TX and RX. The two RX antennas are rotated 45 degrees with respect to each other in order to get a smoother representation of the horizontal pattern when combined.

To verify and validate the setup, a LOS short range (5-40 m) measurement was carried out in an open space to avoid strong reflections. By assuming free space (FS) path loss under these conditions (below the flat-earth breakpoint distance, which is 293 m for 1.9 GHz and 539 m for 3.5 GHz), the system was shown to perform omnidirectionally in both azimuth and elevation for distances larger than 20 m, with the

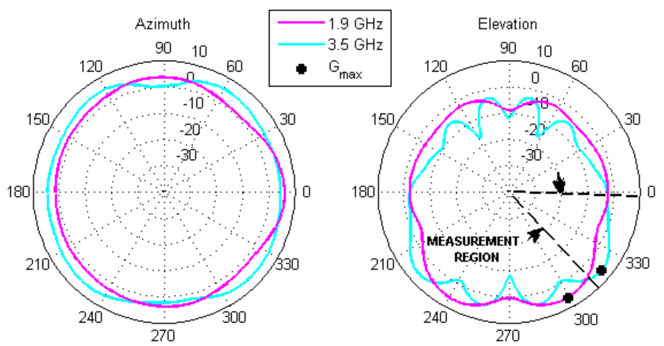

Fig. 2: Theoretical radiation pattern at 1.9 GHz and 3.5 GHz. Azimuth, elevation and measurement region.

measured effective antenna gain value (G_{meas}) presented in Table I for the two frequencies. This value is computed as the average gain measured for 3 different azimuth positions (0, 90 and 180 degrees) along the full elevation measurement range. The effective gain value is clearly smaller than the maximum gain (G_{max}) indicated in the datasheet for the antenna, but better reflects the elevation region towards 0 degrees where most of the measurements are taken. All the path loss results presented in Section III are calibrated to this effective gain value.

C. Measurement Locations and Procedures

The measurement campaign was performed in Aalborg, Denmark. The environment is a typical urban medium-sized European city where the average building height and the street width are about 12-15 m (3-4 floors) and 20 m, respectively. For this campaign, 6 different locations similar to the one detailed in Fig. 3 were selected.

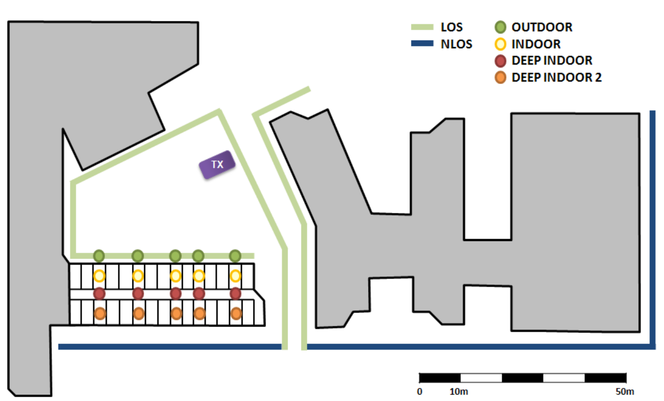

Fig. 3: Location 1. Example of the categorization of the different measurement areas: LOS, NLOS, outdoor and indoor.

Outdoor measurements were done along different routes and categorized according to LOS and NLOS conditions, as illustrated in Fig. 3. Table II lists the LOS and NLOS measurement ranges as well as the indoor scenarios considered at each location. The different routes were covered 2 times, in opposite directions, with the aim of getting more samples and removing the effect of the uneven antenna pattern. The routes were tracked by the internal GPS receiver of the scanner, and from that information, the distance between TX and RX was calculated.

TABLE II: Summary of the different measurement locations.

	LOS Range	NLOS Range	Indoor
Location 1	5-50 m	30-110 m	Modern building
Location 2	5-80 m	30-100 m	Old building
Location 3	2-115 m	100-200 m	-
Location 4	5-70 m	-	2 shops
Location 5	20-100 m	90-160 m	1 shop
Location 6	15-25 m	25-200 m	2 shops

To evaluate outdoor-to-indoor propagation, indoor measurements were conducted inside office buildings (locations 1 and 2, corresponding to a modern building and an old building, respectively) and inside several shops (locations 4, 5 and 6) at ground level. Both office buildings present a similar structure, 3 floors high and similar indoor distribution with offices at both sides of a corridor. In this case, the measurements were done in 5 different points and for 3 different penetration depths, each with increasing indoor distance to the illuminated external wall (yellow, red and orange dots in Fig. 3). For the shops located at street level only the first penetration is investigated in a single measurement point. An overview of the 3 different scenarios (modern building, old building, and shop) can be seen in Fig. 4.

Fig. 4: Overview of the investigated outdoor-to-indoor scenarios.

III. Numerical Results and Discussions

A. Outdoor Propagation

For the outdoor path loss investigation, a separate analysis of the LOS and NLOS categories was carried out. All the path loss samples were calculated from the measurements according to (1) and plotted against the logarithm of the TX to RX distance (d) in meters. The resulting path loss is shown in Fig. 5. Based on a simple linear regression analysis, a path loss model is proposed in (2) for LOS and in (3) for NLOS. It was verified that for both 1.9 GHz and 3.5 GHz, the LOS path loss follows a slope of 20 dB/m (propagation index $n_1 = 2$) and a steeper slope of 40 dB/m (propagation index $n_2 = 4$) for NLOS. The LOS trend found, following the inverse square power law, is in agreement with the previous studies presented in [3] and [4].

$$PL_{LOS}[\text{dB}] = C_1 + 10\, n_1\, log_{10}(d) \tag{2}$$
$$PL_{NLOS}[\text{dB}] = C_2 + 10\, n_2\, log_{10}(d) \tag{3}$$

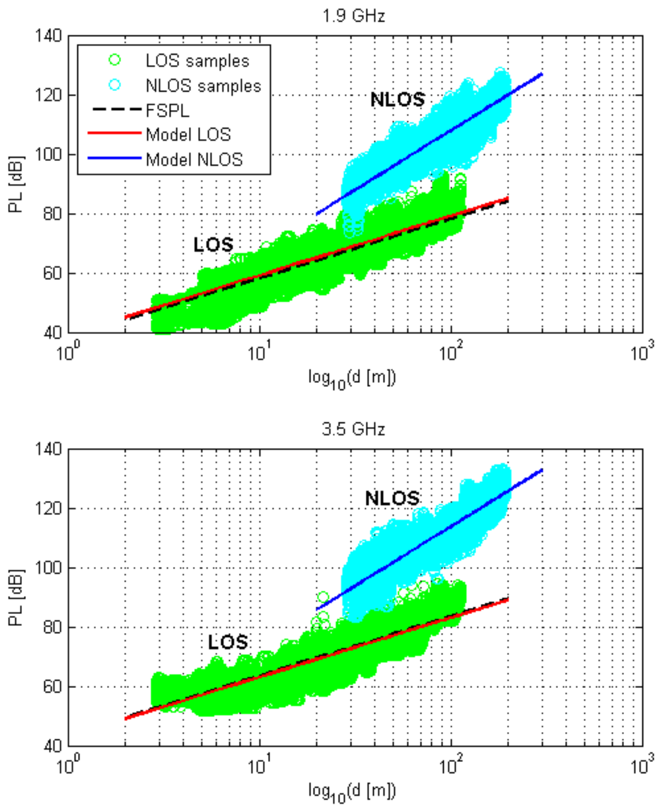

Fig. 5: Path loss samples, FSPL, LOS and NLOS models.

One of the objectives of this paper is to compute the path loss difference between the frequencies, and this information can be extrapolated from the offset coefficients (C_1 for LOS and C_2 for NLOS) indicated in Table III. According to the regression analysis, the mean path loss difference (ΔPL) between 3.5 GHz and 1.9 GHz is in the range from 3.87 dB for LOS and 5.81 dB for NLOS (4.84 dB in average). It is necessary to remark that the LOS path loss, as shown in Fig. 5, is very close to FSPL, similarly to what [5] concluded, with an average deviation of 0.5 dB for 1.9 GHz and -1.22 dB for 3.5 GHz. The error of the different models to the measurements is summarized in Table III. As a reference, other well known measurement-based models for macro cell path loss prediction such as Hata or COST-WI present a mean error of ± 3 dB and a standard deviation (Std) of 3-6 dB in the best case [20, 21]. The previously presented models fit into this range.

TABLE III: Summary of the parameters and the error (Mean and Std) in dB for the proposed LOS and NLOS models.

	LOS				NLOS			
	C_1	n_1	Mean	Std	C_2	n_2	Mean	Std
1.9 GHz	39.06	2	-0.48	3.57	27.69	4	0.03	3.81
3.5 GHz	42.93		-0.65	3.59	33.50		-0.13	3.89
ΔPL	3.87				5.81			

In Fig. 6, existing path loss models are plotted and compared to the proposed models for 1.9 GHz and 3.5 GHz. It has been questioned previously if these models are applicable to the micro cell case [22]. Despite the Hata model is defined for frequencies below 2 GHz, base station antenna height above 30 m and distances above 1 km, quite a good match with the NLOS has been observed for both frequencies in this short micro cell range (Fig. 6). On the other hand, COST-WI clearly overestimates the path loss under these conditions, since it assumes propagation over the buildings and diffraction from rooftop-to-street level so it is clearly unrealistic when the signal clearly propagates along street canyons.

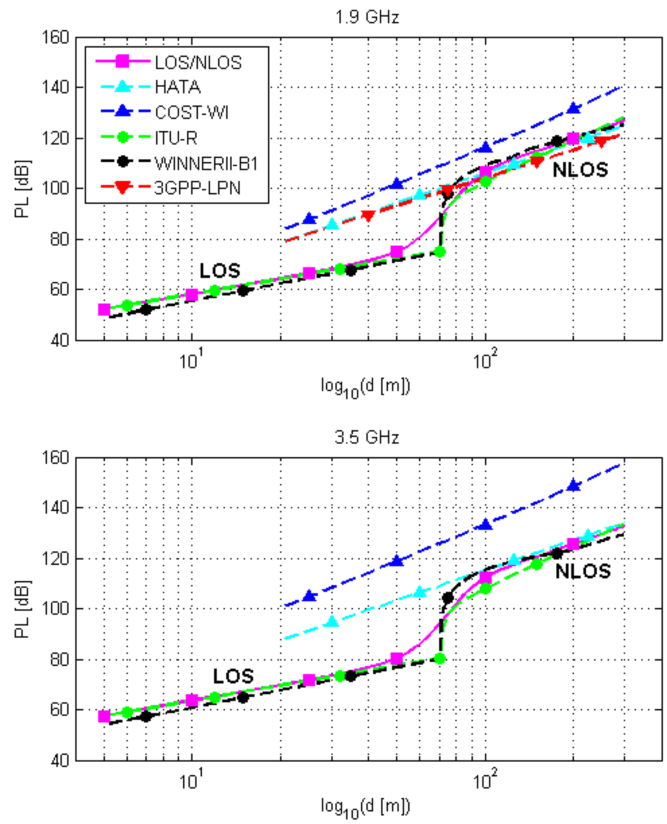

Fig. 6: Comparison between path loss models.

For the specific micro cell scenario, the 3GPP-LPN, defined for a fixed frequency of 2 GHz presents a quite good match to the measured NLOS path loss at 1.9 GHz as shown in Fig. 6. This model could be extended for 3.5 GHz by simply adding a constant offset of approximately 5 dB on top of the model defined at 2 GHz. There exist other models which consider in detail the micro cell scenarios with base stations located well below the rooftop and street canyon propagation, as ITU-R or WINNERII-B1. These models are able to predict the path loss in both LOS and NLOS conditions, but they are difficult to apply from a radio planning perspective, since they base the prediction on two different distances. One distance along the main street canyon and one distance along the perpendicular street after turning at a corner. Hence it is difficult to compute for all the different micro base stations considering the different distances to the corners in a real scenario. In this case, these models have been plotted in Fig. 6 by considering a distance of 70 m along the main street.

A simpler and more straightforward path loss model is presented in (4) and also plotted in Fig. 6. It combines the previously presented LOS and NLOS models in (2) and (3) according to the properties of the micro cell scenario: a clear LOS region close to the base station, a transition area and a NLOS region beyond. The transition from LOS to NLOS is defined through the probability of LOS (p_{LOS}) function in (5) at the particular distance $d_t = 70$ m, which is the intermediate distance between the first NLOS sample (25 m) and the last LOS sample (115 m). This parameter could be tuned to meet the specifications of any other particular scenario, by calculating the average value of the different distances to the first corner present in the scenario, for example.

$$PL[\text{dB}] = PL_{LOS} \cdot p_{LOS}(d) + PL_{NLOS} \cdot (1 - p_{LOS}(d)) \quad (4)$$

$$p_{LOS}(d, d_t) = \frac{1}{1 + ({}^{1}/_{exp\,(-0.1(d\,-\,d_t))})} \quad (5)$$

B. Outdoor-to-Indoor Propagation

For inside-building coverage estimation, typically an offset value is added on top of the predicted outdoor path loss. This value accounts for the outdoor-to-indoor propagation loss, sometimes also referred to as penetration loss (L_P) and can be very different depending on the frequency or building materials and structure. Penetration loss is calculated in (6) as the difference between the mean power level measured outside of the building ($P_{RX\_outdoor}$) and the mean power level measured inside of the building (P_{RX_indoor}) at the different positions illustrated previously in Fig. 3.

$$\begin{aligned} L_P[\text{dB}] &= PL_{indoor} - PL_{outdoor} \\ &= P_{RX\_outdoor} - P_{RX\_indoor} \end{aligned} \quad (6)$$

For each considered point, the mean power level was computed as the average power measured over a 5 m line parallel to the buildings external wall (outdoor) or along a corridor (deep indoor); and inside the offices (indoor and deep indoor 2), the power level was computed as the average power measured inside of the room.

Fig. 7 shows the average value of penetration loss for locations 1 and 2 (modern and old building) calculated from the 5 different measurement points for the different levels of indoor penetration. As it can be seen, penetration loss increases with frequency, as previously reported in [16], and is found to be approximately 5 dB higher for 3.5 GHz as compared to 1.9 GHz. The different values from the modern building and old building can be explained by the different building materials. In the modern building, the external wall is a thick wall made of reinforced concrete with thick glass aluminum-framed windows. This leads to a 10 dB higher attenuation compared to the old building in which the external wall is much thinner and the windows are wood-framed (see Fig. 4). By comparing the different indoor transitions (from indoor to deep indoor and from deep indoor to deep indoor 2), it can be deduced that the indoor propagation is very similar in both buildings and for both frequencies, similarly to what is suggested in [12] and [15]. For example, in the modern building, the penetration loss increment measured from indoor to deep indoor is 6.27 dB at 1.9 GHz and 6.52 dB for 3.5 GHz, very similar to the old building where this measured increment is 5.44 dB for 1.9 GHz and 6.07 dB for 3.5 GHz. This fact can also be explained since both buildings present a similar indoor distribution and the materials of the indoor walls and doors are very similar.

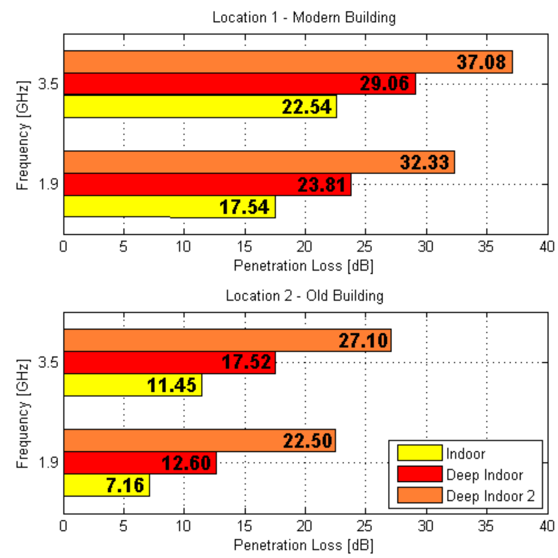

Fig. 7: Penetration loss for different levels of penetration in a modern and an old building.

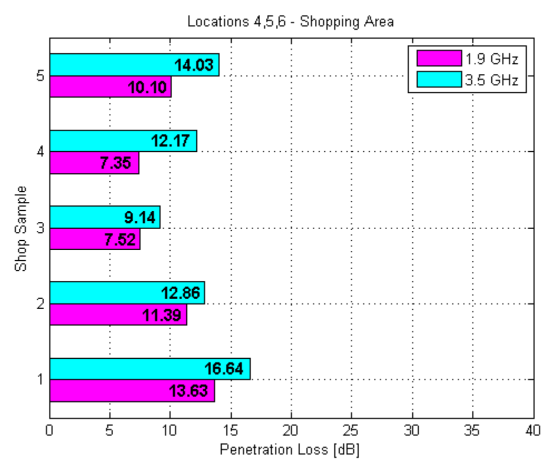

Fig. 8: Penetration loss into different shops.

For the shop scenario, the penetration loss must be considered differently from the previous building scenarios, due to the different wall or facade composition (see Fig. 4). In this case, the signal penetrates into the shop mainly through glass and sometimes even the doors are open which further lowers the attenuation. For this reason, the penetration loss is found to be lower than in the modern building case but due to the thicker glass and the presence of metal-framing windows, this shop scenario present a higher attenuation than the old building case.

From the values of penetration loss measured in the 5 different shops, shown in Fig. 8, it can be seen that the penetration loss for this scenario also increases with frequency (in average, 3 dB higher at 3.5 GHz as compared to 1.9 GHz).

Finally, Table IV presents a summary of the different outdoor-to-indoor penetration loss values observed in the different cases studied in this paper, as well as the difference between this value at the two frequencies (ΔL_P).

TABLE IV: Average outdoor-to-indoor penetration loss measured for the different scenarios.

	Modern building	Old building	Shops
1.9 GHz	17.54 dB	7.16 dB	10.00±2.66 dB
3.5 GHz	22.54 dB	11.45 dB	12.97±2.73 dB
$\mathbf{\Delta L_P}$	5 dB	4.29 dB	2.97 dB

IV. Conclusion

This paper presented an overview of the propagation at 3.5 GHz compared to 1.9 GHz for micro cells in urban scenarios. The analysis focused on the different outdoor and outdoor-to-indoor propagation aspects and path loss differences between both frequencies. For outdoor coverage prediction, a dual slope line-of-sight/non-line-of-sight path loss model, which captures the essence of the micro cell scenario, is proposed and compared to some well known state of the art models. It can be concluded from the presented measurements that, for outdoor micro cells the path loss is approximately 5 dB higher for 3.5 GHz compared to 1.9 GHz, for both line-of-sight and non-line-of-sight conditions. For the outdoor-to-indoor penetration loss, an increment of 5 dB is present for 3.5 GHz as compared to 1.9 GHz for both modern and old types of building. This is at least in general agreement with existing literature, as well as the considerable variation from building to building that is observed. The external wall of the modern building introduces 10 dB higher attenuation compared to the old building due to the different materials and thickness. Typical shops at street level present an intermediate case, where the attenuation is slightly larger than for the old building, with an increment of 3 dB from 1.9 GHz to 3.5 GHz. The indoor propagation attenuation and indoor wall attenuation is shown to be very similar for both frequencies for the in-building cases, in overall agreement with existing literature. In general, by considering all the different situations analyzed, the indoor coverage is shown to be approximately 8-10 dB lower for 3.5 GHz compared to 1.9 GHz. For future work, an extension of this study for different frequency bands will be considered, together with a deeper analysis of the indoor propagation effects.

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