Ray-Optics Simulations of Outdoor-to-Indoor Multipath Channels at 4 and 14 GHz

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Abstract—Radio wave propagation simulations based on the ray-optical approximation have been widely adopted in coverage analysis for a range of situations, including the outdoor-to-indoor (O2I) scenario. This work presents O2I ray-tracing (RT) simulations utilizing a laser-scanned point cloud of the building interior. The simulated radio channels are compared to their measured counterparts at 4 and 14 GHz in terms of path loss, delay, and angular spreads. Validation of channel simulations for O2I cases is rare, and so far nonexistent for above-6-GHz bands. This work reveals the importance of a floor plan model in channel simulations; it is confirmed that path loss can be replicated with a mean error (ME) under 6 dB utilizing a simple interior path loss model instead of a detailed building interior model. Neglecting to model the interior results in high delay and angular spread errors. By modeling the interior, the RT simulations achieve relative ME of under 10% for delay and angular spreads and under 1.5 dB for path loss. Finally, the effects of multilayered insulating window on propagation simulations are reported. Noticeable variation of the penetration loss on a small change of the incident angle of a propagation path causes path gain changes up to 15 dB.

Index Terms—Outdoor-to-indoor (O2I), penetration loss, point cloud, propagation, ray-tracing (RT).

I. INTRODUCTION

Providing wireless service of sufficient quality to indoor users is an essential goal for network operators. Operators seek to utilize previously unused frequencies, including for example, the above-6-GHz new radio frequency range 2 (NR FR2) [1] in addition to the below-6-GHz legacy NR FR1 [2] radio frequency (RF). In the legacy NR FR1, most indoor users are served by outdoor cellular infrastructure. The same service coverage becomes much more challenging in the FR2, given the higher penetration losses through, e.g., building walls, experienced by radio signals. Additionally, increasing demand for energy efficiency [3] has resulted in better insulation of buildings achieved by multilayered windows and insulating films. This has generated interest in studying indoor coverage for energy-efficient smart cities of the future [4].

To this effect, there is a continued interest in outdoor-to-indoor (O2I) channel measurements [5], [6], [7], [8], [9], [10], [11]. The most commonly reported quantity is effect on signal strength inside while being serviced from outside [9], [10], [11], but many studies also report large-scale parameters (LSPs) of multipath channels such as delay and angular statistics [5], [6], [7], [8].

Given the difficulty involved in conducting large-scale measurement campaigns, measurement-calibrated site-specific simulations are an interesting alternative for coverage estimation. Most published results of wave propagation simulations showcase either wholly outdoor or indoor simulations instead of the O2I case, given that obtaining a complete 3-D model of a building can be more difficult than using exteriors obtainable from public databases. A method that has attracted recent interest is a laser-scanned point cloud of the environment used in ray-tracing (RT) [12], [13], [14], [15], [16], [17]. Laser-scanning can be utilized to obtain a complete model of the building and its floor plan. A number of simulation approaches have been published for O2I scenarios (see [18], [19], [20], [21], [22], [23]). In [18] and [19] ray-based propagation was combined with finite difference methods using floor plan of the building. In [20] and [21] a path loss model was applied to indoor propagation without a model of the building interior. In [22] a “virtual floor plan” was generated to approximate building interior effects on propagation, while Calderon Jimenez et al. [23] utilized a commercial RT tool with complete floor plan of the building. To the authors’ best knowledge, O2I propagation simulations have so far only been compared to measurements in terms of path loss, and only for the below-6-GHz band by e.g. [18], [19], [21], [22], and [23]. Similarly, while many approaches to O2I simulations have been published, the effects of the building interior model on LSP accuracy have not been studied. Effects of insulating structures of windows on propagation simulations and estimated coverage due to penetration loss angular selectivity is a similarly unaddressed question.

To these open questions, the novel contributions of this work are as follows.

1) Results of point cloud RT utilizing a 3-D model of the building interior are presented at two frequency bands, 4 and 14 GHz. The frequency bands were chosen as part of LuxTurrim5G [4] to study O2I coverage at below and above-6-GHz bands. By comparing to measurements,
path loss error is found to be in line with earlier publications reporting O2I channel simulations. Relative error of less than 10% is achieved for delay and angular spreads at both bands, a result so far unaccomplished for the O2I channel.

2) Effects of modeling the building interior on simulated channel LSPs are studied. It is shown that while path loss can be replicated with reasonable accuracy without having knowledge of the building interior, a floor plan of the building is required for accurate delay and angular spreads.

3) Effects of a special multilayered insulating window on the simulated channel are elaborated. It is shown that small changes of the incident angles of propagation paths cause significant changes in channel LSPs and estimated coverage due to penetration loss angular selectivity of the multilayered windows.

The rest of this article is organized as follows. Section II describes the O2I site and its laser-scanned point cloud where spatiotemporal channel measurements were performed for validating the RT results. Section III introduces the point cloud-based RT methods. Section IV presents comparisons between measured and simulated O2I radio channels. This article is concluded in Section V.

II. OUTDOOR-TO-INDOOR PROPAGATION ENVIRONMENT

This section describes the laser-scanned point cloud model utilized in RT and the measured channel data at the same site, which were used as ground truth to optimize and validate RT results.

A. Channel Sounding Campaign

Measured channels are used as a ground truth for RT. The O2I measurement campaign has been the subject of the authors’ previous publications [6], [24], where a more detailed description of the measurement setup, methodology, and site is provided. A total of two transmit (Tx) antenna locations and 69 receive (Rx) antenna locations were measured at center frequencies of 4.65 and 14.25 GHz. The Tx locations were outside the office building and Rx locations were inside the second floor of an office building, distributed across three different rooms. The Tx antenna was elevated using a personnel lift to be on the same level with the Rx antenna. Both measurements used the same bandwidth of 500 MHz. Directionally-revolved channel impulse responses were obtained by mechanically rotating a horn antenna on the Rx side [24].

Fig. 1 shows an exemplary power angular delay profile (PADP) obtained from one of the links. Note that weakest gain of the PADP is limited to −150 dB, a noise threshold determined from the PADP. This is done to highlight the excluded distant paths. Signals exist below this threshold, but they are not considered meaningful to represent. For all following analysis, the studied delay range is limited to up to τ = 350 ns, illustrated with the red dashed line. This is to compensate for the effect of distant buildings which sometimes contribute strong propagation paths [24]. These buildings are not represented in the point cloud model used in RT, and hence measured paths from them were omitted for comparison.

A propagation path is defined as a distinct local maxima in the measured PADP. A search over the PADP [15], [25] derived a set of discrete propagation paths to obtain comparable results to the RT simulations.

B. Point Cloud Acquisition and Processing

The point clouds are captured with a Z + F IMAGER® 5006h 3-D laser-scanner [26]. The device uses movable mirrors to steer a laser beam in different directions to detect distances to reflective surfaces. A number of locations outside the building and inside on the second floor are scanned and combined into a complete model of the environment. Resolution of the point cloud used in this work is approximately 10 cm. To obtain a point cloud appropriate for RT simulations, the following steps were performed.

1) Point clouds obtained outside and inside the office building were aligned and merged into one complete point cloud using common reference points.

2) Vertical interior walls of the second floor and the exterior walls on the level of the Tx-Rx links are extracted from the laser-scanned point cloud by detecting large flat sections [12]. They are shown in Fig. 2 in red and black, respectively, the black wall opposite to the office building being a parking structure. Ceilings and floors of the second floor are removed along with the ground outside the building to reduce the size of the point cloud.

3) Individual trees and their canopies are extracted from the laser-scanned point cloud manually. They are shown in Fig. 2 in various colors.

The complete point cloud model used in RT is shown in Fig. 2. All 69 measured Rx locations across three different rooms are shown with red triangles. Room 1 is a square corner room with triple-glass windows facing the outside housing Rx locations 1–21. Room 2 is a rectangular room with triple-glass housing Rx locations 22–41. The third area

Fig. 1. PADP obtained at 14.25 GHz for link Tx2Rx1. Distant paths and a limit of 350 ns to exclude them is shown with a red dashed line.
consists of a kitchen with a double-glass window facing the outside and a corridor that runs behind rooms 1 and 2, housing Rx locations 42–69. The exterior walls with triple- and double-glass windows are highlighted in Fig. 2.

III. POINT CLOUD RAY-TRACING

This section describes the RT methods for determining propagation paths between the Tx and Rx. Gains of the traced paths are estimated separately as introduced in Section IV. The direct propagation path between Tx and Rx along with specular reflections are considered. Each traced path was subject to determine if it undergoes shadowing due to building walls and vegetation.

A. Direct Path

The direct path between Tx and Rx is determined with the Tx and Rx locations illustrated in Fig. 2. The Tx constitutes a starting point of the propagation path and the Rx its ending point.

B. Specular Reflections

Specular reflection is an interaction of a plane wave with an electrically large surface where the angles of incidence and departure are equal. Our method for detecting specular reflections in a point cloud environment is based on an established technique [12], [15], [27], which utilizes the image method and the first Fresnel zone. Detection of single-bounce specular reflections from a section of a point cloud is illustrated in Fig. 3. An image of the Tx is calculated for each point in the point cloud using its normal vector. To find all valid single-bounce reflected paths, it is determined if the point lies within the first Fresnel zone between the image Tx and Rx, i.e.,

$$d_{1,k} + d_{2,k} - D_{3D,k} \leq \frac{\lambda}{2}$$  \hspace{1cm} (1)

where $D_{3D,k}$ is distance between the Rx and image of Tx corresponding to the $k$th point. As shown in Fig. 3, multiple
The ending point of a starting point $p$ is satisfied by any point $x$ applied, where $K$ points whose position vectors are $p_k$, $1 \leq k \leq K$, if there are points inside the first Fresnel ellipsoid. The previous inequality in (1) can be applied, where $d_1$ and $d_2$ are lengths of the propagation path from a starting point $p_1$ to an end point $p_2$. Similarly, $D_2$ is the distance between $p_1$ and $p_2$ and $\lambda$ is the wavelength. If the inequality in (1) is satisfied by any point $1 \leq k \leq K$, a point of the object is within the first Fresnel zone and the propagation path is considered shadowed.

A thin metallic film, likely for added insulation, was known to constitute a single blocking object. The path length is for points blocking the ray. Once again, $K$ points constitute a single blocking object. The path length is used to apply tree canopy losses based on a per-meter attenuation as described in Section IV-B. The process is illustrated in Fig. 4(a).

Fig. 4. (a) Calculating distance from an object to a ray and (b) propagation distance inside an object.

C. Detection of Shadowing Events

Detecting shadowing events of a propagation path in a point cloud has been presented in [28], [29] to derive the line-of-sight probability. A propagation path is assumed to be shadowed by an object, consisting of $K$ points whose position vectors are $p_k$, $1 \leq k \leq K$, if there are points inside the first Fresnel ellipsoid. The previous inequality in (1) can be applied, where $d_1$ and $d_2$ are lengths of the propagation path from a starting point $p_1$ to an end point $p_2$. Similarly, $D_2$ is the distance between $p_1$ and $p_2$ and $\lambda$ is the wavelength. If the inequality in (1) is satisfied by any point $1 \leq k \leq K$, a point of the object is within the first Fresnel zone and the propagation path is considered shadowed.

Leveraging high level-of-detail inherent to laser-scanned point clouds, two influential geometrical parameters are defined to calculate penetration losses.

1) Distance from the ray to nearby surrounding objects that may shadow the ray, $d_w$. For a single object consisting of $K$ points, the distance between the object and ray is given by $d_w = \min_k |d_k|$, where

$$d_k = p_1 - p_k - ((p_1 - p_k) \cdot r)r$$

(2)

is a vector projecting the point $p_k$ onto the ray, whose offset and propagation direction is given by $p_1$ and $r$, respectively; the operator $(\cdot)$ represents an inner product. The defined ray-object distance is used to obtain the penetration loss estimates by introducing a heuristic scaling factor

$$q = 1 - \frac{d_w}{r_F}$$

(3)

where $r_F$ is radius of the first Fresnel zone at the object. Penetration losses from tree canopies and interior walls are scaled using $q$ to account for the changing size of the first Fresnel zone at different frequencies and propagation distances as detailed in Section IV-B. The process is illustrated in Fig. 4(a).

2) Path length $d$ over which a ray undergoes penetration into an object. Projecting the point $k$ in an object onto the ray, its position vector is given by

$$r_k = p_1 - ((p_1 - p_k) \cdot r) r.$$  

(4)

Its distance along the ray from the Tx antenna is $l_k = |p_1 - r_k|$. With these definitions, the penetration length along the path is given by

$$d = \max_k l_k - \min_k l_k$$

(5)

for points blocking the ray. Once again, $K$ points constitute a single blocking object. The path length is used to apply tree canopy losses based on a per-meter attenuation as described in Section IV-B. The process is illustrated in Fig. 4(b).

IV. COMPARISON BETWEEN RAY-TRACING SIMULATIONS AND MEASUREMENTS

Having traced rays and defined several influential geometrical parameters in Section III, the method to estimate gains of each traced paths is defined in this section. Then the results of RT simulations are compared against the measured propagation channel in terms of its LSPs.

A. Ray-Tracing Simulation Setup

The following assumptions are made regarding structures observed at the measurement site to assign permittivity values to different parts of the environment. Windows of the office building were noted to consist of triple- and double-glass windows as shown in Fig. 5(a) and (b), respectively. The layered window structures were not modeled in the raw point cloud and hence manually measured and modeled by hands. A thin metallic film, likely for added insulation, was known to

| Frequency band | 4 GHz | 14 GHz |
|----------------|-------|--------|
| Concrete       | 5.31 + j0.45 | 5.31 + j0.35 |
| Plasterboard   | 2.94 + j0.14 | 2.94 + j0.09 |
| Glass          | 6.27 + j0.10 | 6.27 + j0.13 |
| Metal          | 1 + j4.50 × 10^8 | 1 + j1.28 × 10^8 |
Fig. 5. (a) Triple-glass and (b) double-glass windows with insulating metallic films, and (c) double-plasterboard interior wall. Thickness of each layer is not to scale.

Exist on the interior side of the outermost window. Based on laboratory measurements, effective thicknesses of the metallic films were known to be 7.6 and 28 nm for the triple- and double-glass windows, respectively. Exact structure of the insulating metal film company-proprietary and hence is not known to the authors, and thus an effective thickness is used.

The simulated penetration loss through the triple-glass window is shown in Fig. 6. The loss through a double-plasterboard interior wall, which does not use a metallic film, is overlaid. Mean penetration losses across each frequency band are shown. The mean value is used in the RT simulations. At the 14-GHz band the loss through a triple-glass window oscillates significantly. A change of approximately 2° in incident angles of a plane wave can result in penetration loss difference of up to 20 dB. The oscillation is not present at the 4-GHz band, nor for the double-glass window which is not shown. This is a consequence of the simulated material parameters and layered structure, combined with wavelength. Significant constructive and destructive interference happens only at the 14-GHz band. Penetration loss through the interior walls has a similar level for both frequency bands.

Interior walls of the building separating office spaces were assumed to be typical plasterboard walls consisting of two layers. This structure is shown in Fig. 5(c). Exterior walls of the building are assumed to consist only of windows for simplicity, although there are wooden window frames and some concrete supporting structures included in the facade. The parking structure located opposite to the office building is assumed to consist of concrete.

Well-accepted ITU-R recommendation P.2040 [30] provides permittivity values and formulas to calculate reflection and transmission coefficients using the multilayer slab model. Permittivity values used in RT simulations are reported in Table I. Roughness of reflecting surfaces is not considered to affect the calculated coefficients.

Specular reflections up to four bounces are simulated, which is the maximum number feasible with the utilized simulation software. Diffractions and diffuse scattering are not simulated. A preliminary study of paths diffracted from the top edge of the window opening was conducted utilizing uniform theory of diffraction (UTD) [31]. It was discovered that they were consistently at least 25 and 30 dB weaker than the direct path at the 4- and 14-GHz bands, and therefore not included to reduce simulation time. Due to being uneven surfaces, trees are assumed not to be sources of important propagation paths. Only interior and exterior walls shown in Fig. 2 are considered as sources of reflected paths. Ceilings and floors of the building are not considered as sources of reflections. Any scatterers, e.g., metallic piping, concealed by the false ceiling of the office are not included in the model as they are not visible to the laser scanner.

While performing RT simulations, two different point cloud models are considered. The first consist of only exterior walls of the office building and nearby buildings. As interior structure of the building is assumed unknown in this case, a distance-dependent path loss model is applied to propagation inside the building [32]. The second model in addition includes all interior walls of the second floor, referred to as full floor plan hereinafter, to test their importance in reproducing the measured propagation channel and its characteristics. For both point clouds a resolution of 10 cm between points is used to guarantee that specular reflections can be modeled from each surface as illustrated in Fig. 3. This was verified by calculating the range of possible first Fresnel zone widths on each surface of the simulation model, which were found to be larger than 10 cm at both frequencies, thus ensuring that the approach in Fig. 3 is valid.

B. Obtaining Tree Canopy Loss

To estimate propagation loss through tree canopies, the direct connection paths between Tx and Rx antennas are analyzed. Note that while well-accepted models exist for tree canopy attenuation [33], new values are estimated in this work.
to obtain the best result. Attenuation in vegetation is known to be a highly site-specific phenomenon. Their excess losses to the free space losses are of interests because they are attributed to penetration of the direct path through different window types, interior walls dividing office spaces and tree canopies. The tree losses are estimated by minimizing the difference between measured and simulated excess losses of all direct connection paths. Separate values are determined for tree canopy loss at the two frequency bands.

Propagation delays $\tau_d$ and azimuth angles of arrival $\phi_d$ of direct paths are determined geometrically from the Tx-Rx floor plan of the measurements. Note that due to the propagation environment, it is not feasible to assume that the direct path is always the strongest path. Reflected paths can sometimes be significantly stronger. Due to this, the Tx-Rx coordinates have to be used in a more detailed peak search. The reading of gains in the measured PADPs at the delay and azimuth angle serves as the direct path gain estimate. Specifically, fine estimates of the delay and azimuth angle of arrival of the direct path are identified using the measured PADP as

$$\hat{(\tau_d, \phi_d)} = \text{arg} \max_{\tau_d-\Delta\tau \leq \tau \leq \tau_d+\Delta\tau, \phi_d-\Delta\phi \leq \phi \leq \phi_d+\Delta\phi} \text{PADP}(\tau, \phi)$$

where $\hat{}$ indicates an estimate of corresponding variable and $\Delta\tau$ and $\Delta\phi$ define delay and azimuth ranges over the PADP to find a local maximum. The fine estimates are required to account for uncertainty of the Tx and Rx coordinate information which are manually obtained during measurements. Search ranges in the azimuth $\Delta\phi = 5^\circ$ and in the delay $\Delta\tau = 2$ ns are chosen, both corresponding the their respective resolutions of the channel sounding. Measured excess loss of the direct path is estimated by subtracting the free space path loss as

$$L_{ex} [\text{dB}] = -10 \log_{10} \hat{G}_d - 10 \log_{10} \left( \frac{1}{4\pi \hat{\tau}_d c} \right).$$

The excess loss simulated with point cloud RT is given by the generic formula

$$L_{ex, sim} [\text{dB}] = \sum_{i=1}^{N_{wdw,1}} L_{wdw,1}(\theta_{wdw,1,i}) + \sum_{i=1}^{N_{wdw,2}} L_{wdw,2}(\theta_{wdw,2,i}) + \sum_{i=1}^{N_{tree}} L_{tree}(\phi_{tree,i}) \cdot q_{tree,i} + \sum_{i=1}^{N_{iw}} L_{iw}(\theta_{iw,i}) \cdot q_{iw,i}$$

where $L_{wdw,k}, k = 1, 2$ is penetration loss through the triple- and double-glass windows, respectively. Total window penetration losses through $N_{wdw,k}$ Windows are calculated using [30] and the angle of incidence $\theta_{wdw,k,i}$, where the normal and grazing incidence to the window corresponds to 0° and 90°, respectively. Penetration losses through $N_{tree}$ tree canopies are calculated using the canopy loss $L_{tree}$, propagation distance inside the canopy $d_{tree,i}$ and heuristic scaling factor $q_{tree,i}$ described in Section III-C. Penetration losses through $N_{iw}$ interior walls are scaled similarly, where $L_{iw}$ is calculated using angle of incidence $\theta_{iw,i}$ and multilayer slab model [30].

Note that in the case of no penetrations of a particular environmental feature its respective term in (9) is zero.

Tree canopy losses $L_{tree}$ are obtained by minimizing the mean error (ME) between simulated and measured direct path excess losses. The effect of different $L_{tree}$ on the simulated ME is shown in Fig. 7(a). The lowest errors, approximately 0.1 dB, are achieved with canopy losses of 0.9 and 1.8 dB/m for the 4- and 14-GHz bands, respectively. The values are in line with what is recommended in [33].

The measured and full floor plan simulated excess losses of direct paths are shown in Fig. 8. The measured and simulated locations are indexed such that indices 1–69 correspond to links between Rx locations 1–69 and Tx1, and 70–138 correspond to Rx locations 1–69 and Tx2. Different locations inside the building as seen in Fig. 2 are indicated in Fig. 8(b). Shorthand “R1” stands for Room 1, “R2” for Room 2, “K” for Kitchen, and “C” for Corridor. The excess losses are shown with and without the insulating metal films. The former follows trends of the measured direct path excess loss, while the latter fail to reproduce the trend in measurements. Note that sometimes no metal film results in higher losses than with metal film. This is the effect of the simulated layered materials. It is clear that inclusion of the metal film was critical in accurately reproducing measurements.

The measured and simulated excess losses fluctuate strongly for links that belong to Tx2, i.e., 70–138. This because angles of incidence through the triple-glass windows are greater than 45°, evident from Fig. 2. The oscillating penetration loss through the window is seen in Fig. 6, indicating high selectivity based on angle of incidence. This can be used to explain the difference to measurements for the 14-GHz band, as there is some uncertainty between exact Tx and Rx antenna locations. Even small difference between simulated and actual angle can result in a large change in penetration loss. Overall

![Fig. 7. Determining (a) tree canopy loss, used in (9) and (10), and (b) interior propagation loss, used in (10), by minimizing direct path excess loss ME.](image-url)
difference can be attributed to the trees being modeled as homogeneous. Some environmental details are missing from the simulation model, e.g., wooden supporting structures of the windows and structures inside the building. The effect of a concrete support pillar in the facade not included in the model is pointed out for the 14-GHz band.

### C. Obtaining Interior Propagation Loss

To estimate propagation loss inside the building with a per-meter loss, instead of considering wave interaction with interior walls, the direct connection paths between Tx and Rx antennas are analyzed. The procedure is the same as for obtaining the tree canopy loss. In this case, the excess loss simulated with point cloud RT is given by the generic formula

\[
L_{\text{ex,sim}} \text{[dB]} = \sum_{i=1}^{N_{\text{dw1}}} L_{\text{wdw1}}(\theta_{\text{wdw1},i}) + \sum_{i=1}^{N_{\text{dw2}}} L_{\text{wdw2}}(\theta_{\text{wdw2},i}) + \sum_{i=1}^{N_{\text{tree}}} L_{\text{tree},i} \cdot d_{\text{tree},i} \cdot q_{\text{tree},i} + L_{\text{in}} \cdot d_{\text{in}}
\]

where the new variables \( L_{\text{in}} \), a dB/m interior propagation loss, and \( d_{\text{in}} \), propagation distance inside the building, replace the losses from interior walls. Tree canopy loss determined in Section IV-B is used.

The effect of different \( L_{\text{in}} \) on the simulated ME is shown in Fig. 7(b). The lowest errors, approximately 0.25 dB, are achieved with interior losses of 0.5 and 0.6 dB/m for the 4- and 14-GHz bands, respectively. The values are in line with the frequency-independent 0.5 dB/m recommended in [32], although it is for a Manhattan grid layout.

The simulated direct path excess losses obtained with building exteriors and the interior distance-dependent path loss model are shown in Fig. 8. The simulated values follow the measurements well, except for link indices 110–138 at 4 GHz. The Rx is deep inside the building here, and the distance-dependent path loss does not reproduce these particular cases well.

### D. Comparison Metrics

Having obtained the tree penetration and interior propagation losses using direct paths, path loss of the channel is calculated to study efficacy of the RT simulation. The path loss of a link is derived by summing gains of all traced paths up for the link and taking a base-10 logarithm of it. Angular and delay spreads of the channels are calculated according to [34] as well to evaluate efficacy of the RT simulation in terms of multipath richness in the angular and delay domains. Visual comparisons of the measured and simulated power angular profile (PAP) and power delay profile (PDP) are also given. A dynamic range of 20 dB from the strongest propagation path is used for both measured and simulated channels when calculating LSPs.

### E. Correcting for Antenna Location Uncertainty in Channel Sounding

Fig. 6 shows that penetration losses through the modeled layered materials are sensitive to angle of incidence. Combined with uncertainty in Tx and Rx location estimates that were obtained manually during channel sounding, there can be large differences between the simulated and actual penetration losses of a particular path. This can have a large effect on the overall path gain of the simulated channel.

The effect of this sensitivity on channel gain estimates can be demonstrated by an exemplary link Tx2Rx12 at 14-GHz band; see Fig. 2 for the link geometry. The Rx is in Room 1, and the Tx illuminates the building at an angle of incidence approximately at 45°. Angles of incidence of the propagation path fall in the strongly oscillating penetration loss region. The PAP of the link is shown in Fig. 9. Propagation paths simulated with original Tx and Rx coordinates logged during the measurement campaign and the full floor plan model are shown with green. Updated path gains were obtained by adjusting the Tx and Rx locations within 20 × 20 cm² area around a single coordinate where our measurement report indicates as the antenna location, so that the resulting path loss of the channel matches the measured best. The area was chosen heuristically as a reasonable and small enough area where the antenna was manually placed during measurement sessions. The area is less than 3 and 10 wavelengths in size at the 4- and 14-GHz bands, respectively. The effect is summarized in Table II, where only the window penetration loss was modified due to the adjustment. Trajectories of the four propagation paths are drawn in Fig. 10. All of them incident the building at an angle of over 45°. Path 1 is the direct path, while the other are reflections from interior walls of the building. A change of about 1.5° in angle of incidence results in 15-dB change in gains of the path 1 and 2. Angular spread of the measured channel is 42.4°, while the simulated angular spread with original Tx and Rx locations is 53.4°. With the adjusted Tx and Rx locations taking into account the uncertainty of their estimates during channel sounding, the simulated angular spread becomes 40.9°.

The same antenna location uncertainty compensation was performed for all simulated Rx locations at 4- and 14-GHz bands to improve the path loss estimation accuracy. Results of the 20-cm adjustment on channel path loss at 14-GHz band are shown in Fig. 11. There is a considerable improvement

| Tx/Rx location | \( \theta_{\text{wdw1}} \) [°] | \( L_{\text{wdw1}} \) [dB] |
|----------------|----------------|----------------|
| Original       | 55.7           | 41.4           |
| Adjusted       | 54.2           | 26.3           |
| Path 2         | 55.1           | 37.6           |
| Original       | 52.9           | 22.3           |
| Adjusted       | 52.9           | 21.9           |
| Path 4         | 54.6           | 21.3           |
Fig. 8. Measured and simulated excess loss of the direct path at (a) 4- and (b) 14-GHz bands. Simulated excess loss calculated using obtained tree canopy loss and window metal film thicknesses. Annotations are shorthand for locations shown in Fig. 2.

Fig. 9. Effect of a 20-cm adjustment of simulated Tx and Rx12 locations on 14-GHz channel PAP. Paths of interest are indicated.

for links belonging to Tx2 because the building is illuminated at an angle of approximately 45°. Uncertainty in location estimates has a significant effect. The improvement is smaller for the 4-GHz band because the penetration losses oscillate much less. Overall, rms errors (RMSEs) of simulated path loss decreased from 3.1 to 2.9 dB at the 4-GHz band, and from 5.1 to 3.6 dB at the 14-GHz band. It was necessary to compensate for the antenna location uncertainty to perform meaningful comparisons between simulated and measured channels.

F. Channel Simulation Results

Measured and simulated channel LSPs are presented in Figs. 12 and 13. The LSPs are shown for links 1 through 138, with links 1–69 corresponding to Tx1 and links 70–138 to Tx2. Shorthand “RT” stands for RT.

1) Path Loss: Measured and simulated path losses are shown in Figs. 12(a) and 13(a). Path losses obtained with both simulated cases follow trends of the measurement well. Overall, the full floor plan simulation replicates measurements better.

Fig. 12(a) shows that there is a consistent offset of path loss from exteriors RT at 4 GHz. This can partly be explained with missing reflected paths from walls of R1 and R2 as well as adjacent rooms. Additionally, most of the links are in rooms adjacent to the building exterior. The rooms are empty, and in reality the direct paths and reflections from exterior walls propagating in them are not attenuated. Same consistent but smaller offset be seen for the full floor plan from Tx1 to R1.
and R2. It is reasonable to assume that this is a consequence of neglected propagation mechanisms. As seen in Fig. 2, Tx1 transmits to R1 and R2 through many trees. Especially at 4 GHz they can be expected to contribute paths in the form of scattering and diffraction. There is no consistent offset with full floor plan when Tx2 transmits to R1 and R2. As seen in Fig. 2, there is at most one tree between Tx2 and R2, so there are less sources of errors. Nevertheless, there is good correspondence to measured path losses.

Fig. 11. Effect of the 20-cm adjustment of simulated Tx and Rx locations at 14 GHz on simulated channel path loss at 14 GHz.

Large errors from both full floor plan and exteriors RT are observed in the Kitchen at 4-GHz band. Transmitting from Tx1, the error is an overestimation of path loss suggesting missing propagation paths or mechanisms. A possible explanation is scattering from the trees or the building wall that is almost parallel to the direct path from Tx1 to the Kitchen, neither of which are not included in the simulations. Similarly, diffractions from edges of the double-glass window are not included in the simulations. Nevertheless, the Kitchen is an outlier in terms of errors. Transmitting from Tx2, the exteriors RT has a very large error in the Kitchen. This can be attributed to missing propagation paths that enter the building via R2 and are reflected from its walls toward the Kitchen. These paths are included in the full floor plan RT, hence good agreement with measurements.

Fig. 13(a) shows good agreement between measurements and full floor plan RT at 14 GHz. When transmitting from Tx1, exteriors RT path loss exhibits some overestimation particularly in R1 and the Kitchen. This suggests that reflections inside the room and paths from adjacent rooms still contribute to received power, but not as significantly as at 4 GHz. When transmitting from Tx2, exteriors RT shows significant errors while full floor plan RT reproduces the measured path loss well. This is because the building is now illuminated at an incident angle of approximately 45°, while for Tx1 it was closer to 0°. For the exteriors RT case, far fewer paths enter the building, and they seem to fall in high penetration loss parts of Fig. 6. For the full floor plan RT case, the many reflections from interior walls mean that more paths are likely to fall in the narrow, low penetration loss parts of Fig. 6, and deliver power to the Rx. The measured path loss is thus significantly lower and better replicated with the full floor plan RT.

2) Delay Spread: Measured and simulated delay spreads are shown in Figs. 12(b) and 13(b). The results show that delay spread obtained using full floor plan RT follows its measured counterpart well at both 4- and 14-GHz bands. Although the measured trends are replicated well, there are a number of large outlier errors that stand out. The errors can be attributed to missing propagation paths, either due to neglected propagation mechanisms or details of the environment. For example, similar to path loss, noticeably large errors are seen in the Kitchen for link indices 42–50. Although not drawn anywhere, the large outliers there are explained by an RT propagation path that takes a very long trajectory via R1 and Corridor to the Kitchen. Delay spread obtained with exteriors RT consistently underestimates the measured ones, although it seems to somewhat follow the trend. This can be attributed to the large number of missing propagation paths from the building interior. Reflections from only the exterior walls are not enough to accurately replicate the measured delay spread, but they result in delay spreads of slightly lower levels.

3) Angular Spread: Measured and simulated angular spreads are shown in Figs. 12(c) and 13(c). Full floor plan RT replicates the measured angular spread of many individual links and trends well. Exteriors RT fails to reproduce the measured angular spread completely. The reason for exteriors RT having some success with delay spread but none at all with angular spread is that in delay domain, paths from the exteriors are realistically spread apart. In the angular domain, they are not at all because missing interior means to disregard all propagation paths coming from azimuth angular range between 180° and 360° shown in Fig. 2. The angular spread is therefore significantly underestimated.

4) Paths Originating From Exterior and Interior Walls: Having observed that simulations using only building exteriors underestimate delay and angular spreads, measured and full floor plan RT simulated propagation paths of a specific link are studied next. Fig. 14 shows the PDP and PAP of link Tx1Rx3 at 4-GHz band. The Rx3 antenna is located in R1 at the corner of the office building, while the Tx1 antenna on the other side of a cluster of trees. The Rx3 location inside R1 is shown in Fig. 10, with Tx1 being approximately toward 135°. The strongest paths shown with green circles originate from the exterior walls. Fig. 14(a) shows that after approximately 200 ns, paths bounded on interior walls are required to approximate the measured PDP. Fig. 14(b) shows that paths originating from the exterior walls arrive only from angles between 0° and 180°. To reproduce the PAP from approximately 180° to 360°, paths reflected from interior walls are required.

Measured delay and angular spreads of the link Tx1Rx3 are 29.9 ns and 46.9°. With the full floor plan, the simulated delay and angular spreads are 34.6 ns and 49.8°. While with the exterior wall only, the simulated delay and angular spreads are 19.4 ns and 17.0°. This further demonstrates that interior paths are required for increased accuracy in reproducing the delay and angular spread values.
Fig. 12. Measured and simulated 4-GHz channel (a) path losses, (b) delay spreads, and (c) angular spreads.

Fig. 13. Measured and simulated 14-GHz channel (a) path losses, (b) delay spreads, and (c) angular spreads.

5) Estimation Errors of LSPs: Comparison of the measured and simulated LSPs is summarized in Table III. The mean and standard deviations of the measured and simulated LSPs are shown, as well as the ME and RMSE of the simulated results against measurements derived from all Tx-Rx links. The positive ME means that the simulated LSPs are greater
Table III

| Frequency band | 4 GHz | 14 GHz |
|----------------|-------|--------|
| PL [dB]        |       |        |
| Mean value     | 94.6  | 100.3  |
| Standard deviation | 5.9  | 6.8    |
| Mean error     | n/a   | n/a    |
| RMS error      | 2.9   | 6.6    |
| RMS error      | n/a   | n/a    |

Table IV

Comparison of this work to previously published O2I simulations that were validated with measurements. The table reports ME and RMSE for three LSPs. Entry of n/a means no value was reported.

| Reference | Frequency | Path loss [dB] | Delay spread [ns (Rel.)] | Angular spread [° (Rel.)] | Note |
|-----------|-----------|----------------|----------------------------|---------------------------|------|
| [18]      | 3.5 GHz   | ME 0.09        | ME 2.39                   | n/a                       | RT outside & finite difference inside with one level floor plan. |
| [19]      | 2.4 GHz   | n/a            | n/a                       | n/a                       | RT to building w/ single room. |
| [21]      | 855 MHz   | n/a            | n/a                       | n/a                       | No floor plan, PL model applied inside building. |
| [22]      | 850 MHz   | n/a            | n/a                       | n/a                       | Multi-story virtual floor plan. |
| [23]      | 0.85 GHz  | n/a            | n/a                       | n/a                       | Floor plans, mean error ranges across 5 floors. |
| This work | 4 GHz     | 1.4 2.9        | -2.1 (-8.3%)              | 6.1 (23.6%)               | Point cloud RT using full floor plan of one building level. |
|           | 14 GHz    | 0.3 3.6        | 1.2 (6.6%)                | 8.5 (45.8%)               | Point cloud RT using full floor plan of one building level. |

than those of measurements. The ME encompasses accuracy of the channel simulation overall, whereas the RMSE indicates link-specific accuracy. Standard deviation of the LSP provides the range of values in our O2I site.

Estimation errors of path loss with full floor plan RT and exteriors RT are shown in Fig. 15. The errors follow a Gaussian trend. It can be seen that including the full floor plan reduces the mean value and standard deviation of errors at both frequencies. Path loss overestimation is mitigated with full floor plan RT, indicating that signals originating from the building interior are often important. Overall statistics of the channel in Table III show that path loss ME of 1.4 and 0.3 dB is achieved using the full floor plan RT at the two bands. ME is less than 6 dB for both frequency bands using exteriors RT. Similarly, the RMSEs of path loss are much lower for the full floor plan RT over exteriors RT. Using full floor plan RT
discussed in Sections IV-F2 and IV-F3 the MEs are much lower for exteriors RT. The relative RMSE of delay and angular spreads are high at both frequency bands, tens of percentage points, even when using the full floor plan. This suggests that while the channel is well reproduced on average, the link-specific values are much more difficult to duplicate. This can be explained by simplifications made during RT simulations. Wooden window frames and a few concrete supporting structures in the building facade were ignored by assuming that propagation paths always enter through a window. For example, a reflection from the parking structure, shown in Fig. 2, could be blocked and heavily attenuated by a concrete pillar for one Tx-Rx link but not the next one in the measurements. This effect cannot be reproduced in the simulation due to the assumed homogenized window wall of the building exterior. It is assumed that tree canopies are homogeneous. The mean effect is well reproduced, but in reality a large branch can block a propagation path while another one passes through some leaves. Similarly it was assumed that the interior walls are homogeneous double-plasterboard walls with an air gap. In reality there are some variations in materials, and the air gaps may contain electrical installations and supporting structures. Another simplification of the RT simulations was calculation of only direct and reflected paths, which is a reasonable explanation for the high RMSE of delay and angular spreads. They are far more sensitive to individual propagation paths and their gains. Nevertheless, even with the simplification, the radio channels are well reproduced, suggesting that the direct and reflected paths are still clearly dominant propagation mechanisms over diffuse scattering and diffractions. While diffraction is known to be an important mechanism in non-line-of-sight conditions, many of the Rx locations are essentially within obstructed line-of-sight of the Tx with a window and some canopy between them. However, no more can be said without further study.

Finally, the measured standard deviation of LSPs are reproduced well by full floor plan RT. They vary in a range that is similar to the measured results. Using exteriors RT, the standard deviation is not as well reproduced. This can be explained with the less realistic modeling of multipath richness.

G. Comparisons to Previous Works

Results presented in this work are summarized in Table IV and compared to previously published O2I simulations that were validated against measurements. While a large number of O2I simulations have been performed and published, validation against measurements is lacking in general. Moreover, this work for the first time in the literature performs the validation for above-6-GHz RF. Table IV shows that path loss RMSEs achieved in this work are in line with earlier works. Table IV also includes comparisons of the delay and angular spreads for the first time in the literature, showing sub-10% MEs of the simulated values in reference to the measurements. It is difficult to assess how good or bad the RMSEs of tens of %-points are due to lack of earlier publications. The absolute values are for the most part less than approximately 10 ns or 10°.

V. CONCLUSION

This work presents comparisons of O2I RT simulations and measurements performed at 4- and 14-GHz bands utilizing a laser-scanned point cloud. The measurements were conducted at a typical office building with windows covering the exterior and many rooms separated with plasterboard walls. Measured and simulated direct path excess losses were first used to determine distance-dependent propagation losses inside tree canopies and the office building interior. The values were then applied to ray-traced propagation paths with up to four reflections. RT simulations were performed with two setups; using only exterior walls with no knowledge of building interior and using full floor plan of the level housing Rx antennas. For the former case, the determined interior loss was applied to propagation inside the building in place of a specific floor plan.

Results from the two RT setups were compared with their measured counterparts in terms of channel LSPs to benchmark the accuracy and importance of building floor plan in reproducing measured channels. The results confirm that it is possible to reproduce the measured path loss to a reasonable degree with an ME of less than 6 dB at both 4- and 14-GHz bands. A full floor plan reduces the error to under 1.5 dB at both frequency bands. The path loss errors achieved in this work are in line with earlier publications utilizing various approaches to O2I simulations, although the validation at above-6-GHz band is a new achievement.
Conversely, delay and angular characteristics of the channel cannot be accurately reproduced without a floor plan of the building. To this effect, this work reports a first validation of simulated delay and angular spreads at both above and below-6-GHz bands. A relative ME of less than 10% can be achieved after a careful consideration of the building window types. It was shown that penetration losses of multilayered insulating windows fluctuate strongly across incident angles. This in turn results in large changes in simulated propagation path gains and coverage due to high angular selectivity of the window. This was compensated with small adjustments of the simulated Rx antenna locations to accurately replicate measurements. The RMSE of simulated delay and angular spreads was much larger than MEs at both bands, but maintained under approximately 10 ns and 10°. This indicates that while good overall results were achieved with interactions limited to reflections, further study of diffraction and diffuse scattering as O2I propagation mechanisms is required.

In the future energy efficiency requirements imposed on buildings can be expected to increase further. This can lead to, e.g., in cold climate countries such as Finland, an increased number of triple-glass windows, upgrades to four glass panes, and possibly multiple metal films for added insulation and penetration loss. This warrants special considerations and further study of planning and simulating O2I coverage.

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