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Wave Scatterer Localization in Outdoor-to-Indoor Channels at 4 and 14 GHz

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Abstract—In this paper, we present the results of wave scatterer localization at 4.65 and 14.25 GHz in an outdoor-to-indoor scenario at a traditional office building in Finland. The localization is based on a single-bounce model of interaction with a scatterer to localize the sources of measured multipath components. The estimated scatterer locations were mapped to an aerial photograph of the site and classified according to their location. We found that approximately two thirds of paths originate from higher order interactions with the environment. In contrast, one third of paths can be attributed to single-bounce interactions, with interior walls of the building being twice as strong sources of single-bounces as walls outside both in terms of power and number of paths.

Index Terms—Radio propagation, outdoor-to-indoor (O2I), localization, scattering.

I. INTRODUCTION

Fifth-generation cellular networks currently undergoing deployment hold a promise of higher data rates over their predecessor. One of the techniques enabling the increased data rates is through the use of radio frequencies higher than 6 GHz in addition to the legacy below-6 GHz frequency bands. Given ubiquity of mobile devices, many users of wireless communications will be located indoors rather than outdoors. Cellular operators have a vested interest in ensuring stable communications from an outdoor base station to an indoor hotspot or an individual user. This has resulted in continued interest in outdoor-to-indoor (O2I) radio channel behavior in the form of radio wave penetration losses through building materials [1] and radio channel measurements [2], [3].

In addition to effects of the environment on total signal strength, it is vital to understand where multipath components, hereon referred to as paths for short, originate from. Each scatterer in the propagation environment and combinations thereof will contribute paths at the receiver, resulting in constructive and destructive interference that affect performance of the mobile device. Locations of scatterers in relation to a transmitter (Tx) and receiver (Rx) of a mobile link have long been of interest to the field of wireless communications due to its importance in creating realistic channel models for mobile environments [4]. Experimental results on scatterer localization have been published [5], [6] providing important insights in locations and characteristics of scatterers in different environments. A single-bounce model for locating scatterers based on measurements was introduced in [5], and recently applied to outdoor measurements to locate scatterers [6].

In this paper, we present results of single-bounce scatterer localization performed for an O2I scenario at frequencies of 4.65 and 14.25 GHz. In the context of this paper, a scatterer is the source of a measured path other than the direct path. The scatterers are located based on spatio-temporal channel sounding performed at the aforementioned frequencies at a traditional office building in Finland. The method for scatterer identification is described and applied to paths extracted from channel measurements. The scatterers are classified by superimposing them on an aerial map of the area to study which features of the environment are important sources of single-bounce scattering. The results show that walls of buildings next to the one where an indoor user is located can contribute strong single-bounce paths, even when they are up to 100 m away. Similarly, interior walls dividing office spaces are significant sources of single-bounce paths. On average, approximately 37.3% and 40.6% of power from measured paths at 4.65 and 14.25 GHz, respectively, is accounted for by single-bounce scattering from features of the environment we deem prominent, i.e., building walls and tree canopies. The results provide important information for future efforts to develop geometry-based stochastic O2I channel models; more than single-bounce scattering must be considered to reproduce observed multipath richness.

The remainder of the paper is structured as follows. Section II describes the channel sounder used during the measurements and the O2I propagation environment. Section III describes the method for scatterer localization based on a single-bounce model. Section IV analyzes the scatterer locations in relation to floor plan of the measurement site and discusses the results. The paper is concluded in Section V.

II. OUTDOOR-TO-INDOOR CHANNEL SOUNDING

In this Section the channel sounder is described, along with the measured O2I scenario.

A. Channel Sounder

The channel sounder is based on a vector network analyzer (VNA) that allows phase-synchronized measurements of radio channels. In this paper we have chosen the below and above 6 GHz frequency bands 4.4–4.9 and 14.14-15 GHz, with respective center frequencies of 4.65 GHz and 14.25 GHz. To allow measurements of long link distances, the sounder is equipped with 1) optical fiber cables to replace lossy coaxial cables at the frequency bands and 2) a directive high gain...
Fig. 1: A birds-eye view of the measurement site. Shown on the Figure are two measured Tx locations and 69 measured Rx locations inside the building. Reference directions of $\phi$ are illustrated in the upper left of the Figure.

![Fig. 1](image1.png)

Fig. 2: Exemplary power angular-delay profile for Tx1-Rx8 link at 14.25 GHz. Red triangles show results of a peak search performed on the PADP.

![Fig. 2](image2.png)

antenna on the Rx side to increase the measurement dynamic range. A log-periodic antenna with about 9 dBi gain and 50° half-power beamwidth (HPBW) in the azimuth and elevation domains is used on the Rx side at 4.65 GHz, while a sectoral horn antenna with 19 dBi gain, 10° azimuth and 40° elevation HPBW is used for 14.25 GHz measurements at the Rx. The Tx antennas are different bicone antennas at the two frequencies, both showing omni-directional patterns with 2 dBi of gains to the horizontal directions. All antennas on both the Tx and Rx sides are vertically polarized. The output power of the VNA is $-15$ dBm, and of the optical-to-electrical (O/E) converter $-10$ dBm. Before the Tx antenna an amplifier with 30 dB gain is installed, bringing total power fed to Tx antenna port to approximately 20 dBm at both frequencies. During measurements dynamic range of channel impulse responses is 138 dB and 147 dB at 4.65 GHz and 14.25 GHz, respectively. Intermediate frequency (IF) bandwidth of the VNA is chosen as 1 kHz at both frequencies. Measuring a single Tx-Rx link consists of rotating the directive Rx antenna over 360° in azimuth angle $\phi$ steps of 5°. This collection of angle-dependent impulse responses of the channel gives a Power Angular Delay Profile (PADP) for each Tx-Rx link. Figure 2 shows an exemplary PADP obtained from one of the links. The PADP resolves multiple propagation paths over angle and delay. All propagation paths observed in the PADP undergo penetration through some parts of the building facade and are subject to varying excess loss compared to free-space path loss (FSPL). The losses depend on a path’s geometrical relation to the nearby buildings and interiors of the office building. Relevant parameters of the channel sounder are summarized in Table I.

### TABLE I: Summary of channel sounder parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$f_c = 4.65$ GHz</th>
<th>$f_c = 14.25$ GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>0.5 GHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>IF Bandwidth</td>
<td>1 kHz</td>
<td></td>
</tr>
<tr>
<td>Frequency points</td>
<td>1001</td>
<td></td>
</tr>
<tr>
<td>Delay resolution</td>
<td>2 ns</td>
<td></td>
</tr>
<tr>
<td>Maximum delay</td>
<td>2000 ms</td>
<td></td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>5°</td>
<td></td>
</tr>
<tr>
<td>Tx antenna port power</td>
<td>20 dBm</td>
<td></td>
</tr>
<tr>
<td>Tx antenna (gain)</td>
<td>Bicone (2 dBi)</td>
<td></td>
</tr>
<tr>
<td>Rx antenna (gain)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx antenna az. HPBW</td>
<td>Log-periodic (9 dBi)</td>
<td>Sectoral horn (19 dBi)</td>
</tr>
<tr>
<td>Rx antenna el. HPBW</td>
<td>50°</td>
<td>10°</td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>50°</td>
<td>40°</td>
</tr>
</tbody>
</table>

B. Channel Sounding Campaign

The O2I channel sounding was performed in a traditional four-story office building from 1980’s made of bricks and glass windows in Karaportti, Espoo, Finland. The measurement site is depicted in Fig. 1 from a birds-eye view. Two measured Tx locations outside the office building are indicated. Inside the building on the second floor are 69 Rx locations in three different rooms with the antenna approximately 1.7 m from the floor. Interior of the building is separated into workspaces and meeting rooms with plasterboard walls. The Tx antennas were elevated so that they were on the same level with the Rx antenna, approximately 4.8 m from the ground. Between the Tx and Rx locations are a number of leaved and coniferous trees. Note that for all measurements, all curtains of the windows were drawn up. At the time, the building was unused and thus largely empty of furniture and pedestrians. Measurements were conducted during summer and the trees
were in full leaf. In total 138 Tx-Rx links were measured at each frequency.

III. SINGLE-BOUNCE SCATTERER LOCALIZATION

In this Section we describe the mathematical method for measurement based single-bounce scatterer localization.

A. Peak Detection

To localize scatterers, we extract a set of discrete paths from each PADP. This is achieved with a search for local maxima in the continuous PADP. The local maxima must be at least 3 dB above their neighboring PADP bins. After extracting paths for a given Tx-Rx link, we enforce a dynamic range of 20 dB down from the strongest path and discard those outside of it.

Each obtained path $\mathcal{P}$ can then be described by $\mathcal{P}_l = \{G_1, \tau_1, \phi_1, \theta_1\}$, where $G_1$ is path gain, $\tau_1$ propagation delay and $\phi_1$ angle of arrival in relation to the reference direction $\phi = 0^\circ$ shown in Fig.1. For proper application of the single-bounce model, we also define $\theta_1$ as angle of arrival in relation to the direct path between Tx and Rx. Delay and angle of arrival of the direct path is extracted from the floor plan of the measurement campaign. Results of a peak search are shown in Fig. 2 with red triangles along with $\theta_1$.

B. Single-Bounce Model

Scatterers can be located given a set of paths with angles of arrival and excess delays in relation to the direct path. The method is based on the assumption that each path is the result of a single-bounce interaction with a scatterer. A solution to the problem is illustrated in Fig. 3, where excess propagation distance $d = r_1 + r_2 - s$ of a path defines an ellipse on which the scatterer lies with Tx and Rx at its focii. Note that for clarity the subscript $l$ has been omitted. Angle of arrival in relation to the direct path $\theta$ allows us to locate the scatterer. In reality, there is some $z$-axis difference between $p_{\text{Tx}}$, $p_{\text{Rx}}$ and the scatterer $p_{\text{sca}}$. To simplify the problem we assume that they all lie on the same plane, i.e. angle of arrival in relation to the direct path $\theta \approx \theta^\perp$, where $\cdot^\perp$ denotes projection to the $xy$-plane.

The major axis of the ellipse along the direct path can be expressed as $a = (s + d)/2$ and its eccentricity as $e = s/(s + d)$. Using a well-known identity of the ellipse, we can solve distance $r_1 = |p_{\text{sca}} - p_{\text{Rx}}|$ from

$$r_1 = \frac{a(1 - e^2)}{1 - e \cos(\theta)} = \frac{2sd + d^2}{2s + 2d - 2s \cos(\theta)}. \tag{1}$$

Given coordinates of the Tx and Rx for each path, we can plot and analyze the scatterers on a map of the environment.

C. Excess Loss Estimation

To quantify the significance of the scatterer, we account for the free space path loss (FSPL). We can write excess loss of the $l^{\text{th}}$ propagation path as

$$L_{\text{ex},l} = 20 \log_{10}(4\pi \tau_l f_c) - G_{l[\text{dB}]} \tag{2}$$

Note that this is not excess loss from single-bounce via the scatterer alone, but includes penetration losses through other parts of the environment.

IV. RESULTS

In this Section, we present and discuss results of scatterer localization at 4.65 GHz and 14.25 GHz.

A. Distant Scatterers

All scatterer locations based on Eq. 1 are shown in Fig. 4 superimposed on a map of the location showing an area of 300 m by 300 m. The scatterers can clearly be categorized as being near or distant. The distant scatterers coincide with locations of relatively distant buildings. For $f_c = 14.25$ GHz, they also have mirror images at the opposite side of the near scatterers. They are likely produced by a double reflection from the building and a wall of the room housing the Rx. For $f_c = 4.65$ GHz, they are more dispersed and the wedge-like building appears to produce no single-bounce paths. Furthermore, single-bounces from distant buildings have low excess losses of 20-35 dB, signaled by the red hues. Near scatterers appear to be dominated by hues of blue at $f_c = 14.25$ GHz, but more green and orange at 4.65 GHz. Near scatterers for both frequencies appear all to be contained by a circle with approximate radius of 50 m that encloses the Tx and Rx locations. We next focus on the near scatterers and their distributions.

B. Near Scatterers

Figure 5 shows scatterers superimposed on a floor plan of the measurement site. Results obtained for $f_c = 4.65$ GHz are shown in Fig. 5(a), and $f_c = 14.25$ GHz in Fig. 5(b). Color and size of the scatterers indicate excess loss of the path originating from them; larger and redder means more significant scatterer. Note that different scaling is used for the two frequencies to maintain readability.

From Fig. 4(b) we can see that many strong scatterers are located outside the building. They appear co-located with wall of the parking structure, office building wall opposite to the measured rooms and the glass walkway connecting the buildings. These scatterers exhibit excess losses of approximately 20-35 dB. A number of strong scatterers can be seen to
Fig. 4: Near and distant single-bounce scatterers detected from channel sounding at \( f_c = 4.65 \) GHz (a), and \( f_c = 14.25 \) GHz (b). Coloring indicates excess loss of the path originating from the scatterer. Red means stronger scatterer.

Fig. 5: Single-bounce scatterers near the Tx and Rx locations at \( f_c = 4.65 \) GHz (a) and \( f_c = 14.25 \) GHz (b). White stars denote measured Tx locations and the squares Rx locations. Coloring indicates excess loss of the path originating from the scatterer. Red means stronger scatterer.
coincide with interior walls of the office building, suggesting that they are sources of strong single-bounce paths. A large number of weaker scatterers appear not to coincide with any of the interior walls, suggesting they are single-bounces from features not shown on the floor plan or multi-bounce paths.

Scatterer locations obtained from $f_c = 14.25$ GHz measurements are contrasted with $f_c = 4.65$ GHz results shown in Fig. 5(a). The strongest scatterers appear co-located with the northernmost tip of the parking structure near Tx2 and walls of the corner room. An arc of strong scatterers is formed around the corner room. Most of them are not co-located with interior walls, which suggests that they are likely multi-bounce paths that are not valid for the presented single-bounce model. A number of strong scatterers can be seen to the south of the region, near the glass walkway.

C. Discussion

Type and origin of the scatterers can be estimated by comparing their locations with prominent features of the measurement site. First, we define outlines of building walls nearby and distant to Tx and Rx, and outlines of interior walls. If a scatterer coincides with one of these, we classify it as a single-bounce from its respective source. Secondly, we define regions with tree canopies between the Tx and Rx. If a scatterer coincides with these regions, we classify it as single-bounce from a tree canopy. We give a heuristic 0.3 m margin around the respective regions in line with delay resolution of the channel sounder. If a scatterer does not coincide with any of the aforementioned features, we cannot classify it using the present method. The results of this analysis are summarized in Table II for path types as a share of the received power from multipaths and the total number of paths, with the direct path excluded.

The results show that on average interior walls of the building are approximately twice as strong sources of single-bounce paths than walls of other buildings both in terms of power and the number of paths. However, in an extreme case at 14.25 GHz single-bounces from the distant buildings can account for up to 48.6% of multipath power, signaling that they can have a strong effect on the channel. At 4.65 GHz, the distant buildings have a much lower maximum contribution of 5.0% multipath power. Tree canopies are not very strong sources of single-bounce paths. Both frequencies are dominated by path types that cannot be classified as single-bounce, as approximately two thirds of multipath power and raw path numbers belong to them. In extreme cases, paths other than single-bounces from prominent features of the environment can account for over 90% of paths.

V. Conclusion

In this paper we have presented scatterer localization for an O2I scenario at two different frequency bands, centered at $f_c = 4.65$ GHz and 14.25 GHz. Our analysis was based on the assumption that each path detected from channel measurements was the product of a single-bounce from a scatterer. By comparing the estimated scatterer locations with prominent features of the environment, we have shown that interior walls of the building housing the receiver are approximately twice as strong sources of single-bounce paths than walls of the other buildings. Additionally, trees located outside the building were shown to be weak sources of single-bounce paths. Most paths were not classifiable using a single-bounce model, accounting for two thirds of all multipath propagation. These observations hold for both studied frequencies. These results can act as a reference point in developing future geometry-based stochastic O2I channel models. For a realistic model, higher order interactions must be considered to reproduce the observed multipath richness.

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