Abstract—Ray tracing based on geometric optics can be utilized for generating propagation models for arbitrary and complex environments. These methods can be employed to determine important wireless channel characteristics such as coherence and delay spread. In this paper, an image theory based ray tracing method is used to study ultra-wideband propagation in complex tunnel environments such as curved tunnels and bifurcations. To validate the model, simulation results were compared to the experimental measurements performed in a hallway of an office building.

I. INTRODUCTION

Propagation of wireless signals has been studied theoretically, numerically and experimentally for many years. For several applications of interest, a detailed knowledge of the propagation characteristics of realistic tunnel environments is important [1]. Moreover, the evolution of ultra-wideband (UWB) radio motivates research on the channel impulse response and parameters such as delay spread and coherence of UWB signals in tunnel environments, to characterize them over a substantial frequency range up to 10 GHz. To this end, a 3-D image theory based ray tracer is developed and experimentally validated in this paper. The ray-tracer is subsequently employed to characterize tunnel geometries over the UWB radio frequency band.

II. RAY-TRACING BASED PROPAGATION MODELING

The implementation of the ray tracer is based on the steps outlined in [2]. The simulation environment and parameters are described in text files that are passed onto the ray tracer as inputs. The first step is to compute the image tree which contains the image sources of the original source through each plane present in the environment. The images in turn spawn secondary images and process continues until the desired number of reflections is achieved. All these images and their hierarchy is stored in a tree. Each node in the tree is tested to determine whether it represents a path that exists and if so, whether the path is obstructed by other planes or not. The list of paths that exist are then processed to extract the electric field associated with each path. For an environment that contains $N$ planes and $k$ is the maximum number of reflections allowed, the first level of this tree contains $N$ nodes. The next level contains $N - 1$ images for each of the $N$ nodes and therefore a total of $N(N - 1)$ nodes. The tree contains $k$ levels in total and the $i^{th}$ level contains $N(N - 1)(i - 1)$ nodes. For most practical problems this unoptimized tree can grow very large and hence presents both unrealistic memory and execution time requirements. In order to eliminate the large memory requirement, rather than storing all the image data in a tree, the candidate image source nodes can be computed on the fly and tested. This way only the images which correspond to actual paths need to be stored. This a much smaller number compared to total number of images in the original search space. For simulations, several parameters need to be properly configured. Most importantly, the maximum number of permissible reflections needs to be carefully set. The number of reflections required to converge onto a solution is a function of the separation distance between the transmitter and the receiver, especially in tunnel environments. Using a higher number of reflections provides no significant improvement in the accuracy of the results but takes longer to simulate. To illustrate this, consider a 10 m wide and 5 m wide curved rectangular tunnel with a radius of curvature of 200 m. The Tx is placed at a height of 4.9 m along the central axis of the tunnel 50 m away from the starting of the curved section. The Rx is placed in the curved section 153.79 m away from the Tx at a height of 3 m. The path gain is computed as a function of frequency for different number of maximum reflections and the results are shown in Figure 1. The results have converged showing that 5 reflections are sufficient. To simulate the same problem using 6 reflections takes 3.6 times more time. Another parameter that was swept in this example was the number of rectangular prisms used to approximate the circular arc and it was determined that at least one rectangular prism for each 3° of the arc is sufficient.

III. EXPERIMENTAL VALIDATION

As part of the validation, measurements were performed in an office hallway shown in Figure 2. The Tx and Rx were placed at heights of 1.28 m and 1.36 m respectively. The Tx and Rx were separated by a distance of 22.5 m at their base. Details of the measurement setup and the simulation parameters are provided in the following sections.

A. Channel Measurements

There are various methods to excite the channel to measure its impulse response over the entire UWB frequency band. There are some features of the measurement system to keep in mind:

- Wideband impulse response acquisition capabilities
- Robustness to in-band interference and noise
signal generator which modulated the baseband signal up to a carrier frequency $f_c$. This signal was amplified by a power amplifier before being transmitted by a UWB antenna. Both the transmitting and receiving antennas used were custom-built balanced antipodal Vivaldi antennas (BAVAs), each of which has a $-10$ dB return loss bandwidth from 2.8 GHz to beyond 11 GHz. The received signal from the BAVA was sent through a wideband low-noise amplifier before being fed into a digital store oscilloscope with a real-time sampling frequency of 20 GS/s. The captured data on the oscilloscope was transferred to a computer which processes the received signal and computes the impulse response of the measured channel. A cross-correlation of the input and output of the channel was computed, which is a very close approximation of the channel’s impulse response.

### B. Simulation

For the simulation, the hallway was approximated as a uniform rectangular tunnel with concrete walls, ignoring the fine features such as light fixtures, doors and pillars. The electrical properties of the walls were estimated as $\varepsilon_r = 5$, $\sigma = 0.001$, similar to that of concrete. The maximum number of allowed reflections were varied and it was observed that allowing any more than 6 reflections did not improve the accuracy of the results. This is to be expected, as for a short separation distance of 22.5 m as more reflections are allowed, the paths which undergo more than 6 reflections are much longer than the ones that go through fewer reflections.

The comparison between the measured and simulated is shown in Figure 4. The agreement achieved is quite good despite the fact that a very simple approximation of the hallway is used for the simulation. The pattern of the BAVA antenna is not used for the simulation and instead a dipole antenna pattern is used for the Tx and Rx. The discrepancies can be attributed to the fact that the simulated environment ignores thick concrete pillars, non-uniform materials, BAVA antenna pattern and other sources of leakage such as thin walls.

### IV. APPLICATION OF THE RAY TRACER

Temporal coherence of a signal is an important property used while planning wireless networks. In this...
The tunnel is 10 m wide and 5 m high. There is a 50 m long straight section before the beginning of a 60° circular arc of radius 200 m. The simulation parameters are presented in Table I. The received signals at $R_{x,1}$ and $R_{x,2}$ are shown in Figs. 6 and 7 respectively.

### Table I

**Simulation Parameters of the Curved Rectangular Tunnel.**

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall $\sigma$</td>
<td>5</td>
</tr>
<tr>
<td>Wall $\sigma$</td>
<td>0.001</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1–10 GHz</td>
</tr>
<tr>
<td>Tx height</td>
<td>4.9 m</td>
</tr>
<tr>
<td>$R_{x,1}$, $R_{x,2}$ height</td>
<td>3 m</td>
</tr>
<tr>
<td>$T_x-R_{x,1}$ separation</td>
<td>153.79 m</td>
</tr>
<tr>
<td>$T_x-R_{x,2}$ separation</td>
<td>152.39 m</td>
</tr>
<tr>
<td>Maximum reflections</td>
<td>5</td>
</tr>
</tbody>
</table>

In each figure, the top curve shows a 1 µs simulation window and the bottom curve shows the detailed view of the region showing the arrival of the first pulse. The signal observed at $R_{x,1}$, which is located 1 m away from the side wall of the tunnel, is coherent. However, at $R_{x,2}$, which is approximately the same distance from Tx but closer to the central axis of the tunnel than $R_{x,1}$, the signal received is

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**A. Curved Rectangular Tunnel**

To simulate a curved rectangular tunnel the circular arc is approximated using rectangular prisms. As discussed in Section II, every 3° of the circular arc are approximated using one rectangular prism. A scaled diagram of the simulated environment is shown in Figure 5, which also shows the locations of the transmitter Tx and the two receivers $R_{x,1}$ and $R_{x,2}$.

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Fig. 4. Measured and simulated wideband frequency response of a wireless channel shown in Figure 2.

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Fig. 5. Scaled diagram of the curved rectangular tunnel showing the locations of the Tx (diamond), $R_{x,1}$ (circle), $R_{x,2}$ (square).

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Fig. 6. Curved Rectangular Tunnel: Received signal at $R_{x,1}$, coherent.

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Fig. 7. Curved Rectangular Tunnel: Received signal at $R_{x,2}$, incoherent.
incoherent. This shows that coherence is not a simple function of the distance of the Rx from the Tx but rather also subject to where the Rx is placed along the transverse plane of the tunnel.

B. Bifurcated Rectangular Tunnel

The top view of the bifurcated tunnel geometry is shown in Figure 8. The tunnel is 5 m wide and it is 5 m high. The branched section starts after a 50 m long straight section of the main branch. The branch is at a 45\(^\circ\) angle to the main branch. The simulation parameters are presented in the Table II.

![Fig. 8. Scaled diagram of the top view of the bifurcated rectangular tunnel showing the locations of the Tx (circle), \(R_{x,1}\) (square), \(R_{x,2}\) (diamond).](image)

TABLE II
SIMULATION PARAMETERS OF THE BIFURCATED TUNNEL.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall (\epsilon_r)</td>
<td>5</td>
</tr>
<tr>
<td>Wall (\sigma)</td>
<td>0.001</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1–10 GHz</td>
</tr>
<tr>
<td>Tx height</td>
<td>4 m</td>
</tr>
<tr>
<td>(R_{x,1}, R_{x,2}) height</td>
<td>3 m</td>
</tr>
<tr>
<td>Tx-(R_{x,1}) separation</td>
<td>30.03 m</td>
</tr>
<tr>
<td>Tx-(R_{x,2}) separation</td>
<td>82.09 m</td>
</tr>
<tr>
<td>Maximum reflections</td>
<td>8</td>
</tr>
</tbody>
</table>

The received signals at \(R_{x,1}\) and \(R_{x,2}\) are shown in Figs. 9 and 10 respectively. The signal is not coherent at \(R_{x,1}\) even though it is only 30.03 m away from the Tx. This is due to the fact that the Tx and \(R_{x,1}\) are quite close to the left side wall, Tx is 0.1 m away and \(R_{x,1}\) 1 m. This leads to the singly reflected path off of the left side wall interfering with the direct path leading to the loss of coherence. At \(R_{x,2}\), which is in the branched section, the direct path does not exist. The reflected paths once again interfere to cause a severe loss of coherence. Both these examples show how the time domain results can allow a visibility into the coherence of the received signal.

V. CONCLUSION

In this paper, a 3-D image theory based ray tracer is presented. Preliminary validation is performed by showing a good agreement between measured and simulated results using the ray tracer in an office hallway. The validated ray tracer then is used to study UWB pulse propagation in curved and bifurcated rectangular tunnels. It is shown how the time domain results generated using the ray tracer are useful in determining where in the tunnels the signal loses coherence.

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REFERENCES