



Ultra-Wideband Propagation Modeling in Complex Tunnel Environments using Ray Tracing

Neeraj Sood

Supervisor: Costas D. Sarris

University of Toronto, Canada

February 15, 2011



Outline

- **Introduction – Wireless Channel Modeling**
- **Ray-Tracing**
 - Shoot, Bounce and Reflect (SBR)
 - Method of images (IT)
- **Experimental Validation**
- **Application – UWB pulse propagation**
 - Curved Rectangular Tunnel
 - Branched Rectangular Tunnel
- **Conclusion**



Wireless Channel Modeling

- **Waveguide Theory** provides efficient and accurate results for canonical geometries
- But too restrictive for realistic situations
[Dudley et al., “Wireless propagation in tunnels,” IEEE Antennas and Propagat. Mag., vol. 49, no. 2, pp. 11–26, Apr. 2007]
- **Ray-Tracing** based on Geometric Optics and Uniform theory of diffraction can be utilized to characterize tunnels with arbitrary and complex geometries
- However it is computationally intensive.
[M. Catedra, Cell Planning for Wireless Communications. Artech House, 1999]



Wireless Channel Modeling

- **Vector Parabolic Equation** methods applied to tunnel geometries provide some advantages of full-wave solution without taking as much execution time or memory requirements.
- Although discontinuities or transitions can render the paraxial approximation inaccurate.

[Popov et al., “Modeling radio wave propagation in tunnels with a vectorial parabolic equation,” IEEE Trans. Antennas Propagat., vol. 47, no. 9, Sep. 2000]



Goal

- **Project Goals**

- Develop an accurate and efficient simulation tool to study propagation of wireless signals in complex tunnel geometries such as transitions, bifurcations etc
- Capable of simulating distances of up to 10km
- Capable of simulating frequencies up to 10 GHz

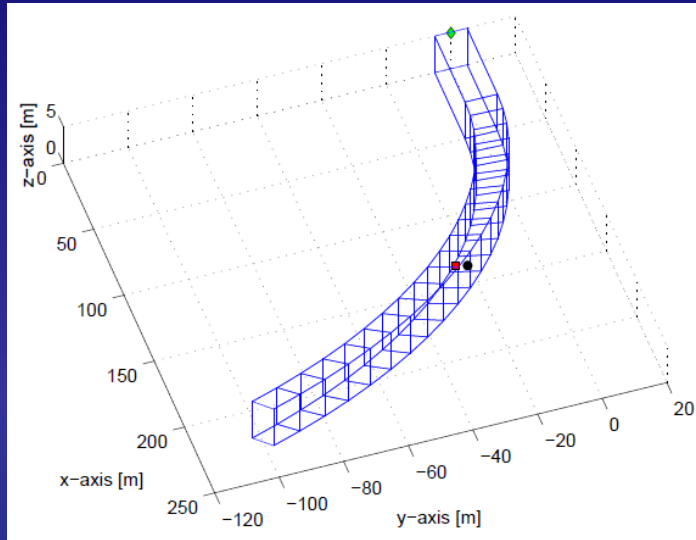
- **A 3D Ray-Tracer**

[H. L. Bertoni, Radio Propagation for Modern Wireless Systems. Prentice Hall PTR, 2000]



Simulator – Overview

- Channel description



```
recursion_level = 5;
number_of_surfaces = 124;
transmitter_location = (0, 0, 4.9);
receiver_location = (152, -23.33, 3);
radiated_power = 1;

sweep_param = freq;
start_frequency = 1000;
end_frequency = 10000;
frequency_incr = 0.25;

surface0
{
  surface_type = FINITE_PLANE;
  outward_normal = (0.000000, -1.000000, 0.000000);
  constant_d = 5.000000;
  rel_perm = 5;
  conductivity = 0.001;
  num_vertices = 4;
  vertices = (0.000000, 5.000000, 0.000000) (0.000000, 5.000000, 5.000000)
(50.000000, 5.000000, 5.000000) (50.000000, 5.000000, 0.000000);
}
surface1
{
```

- Ray Tracing

- Shoot, Bounce and Reflect (SBR)/Method of Images
- Most computationally intensive

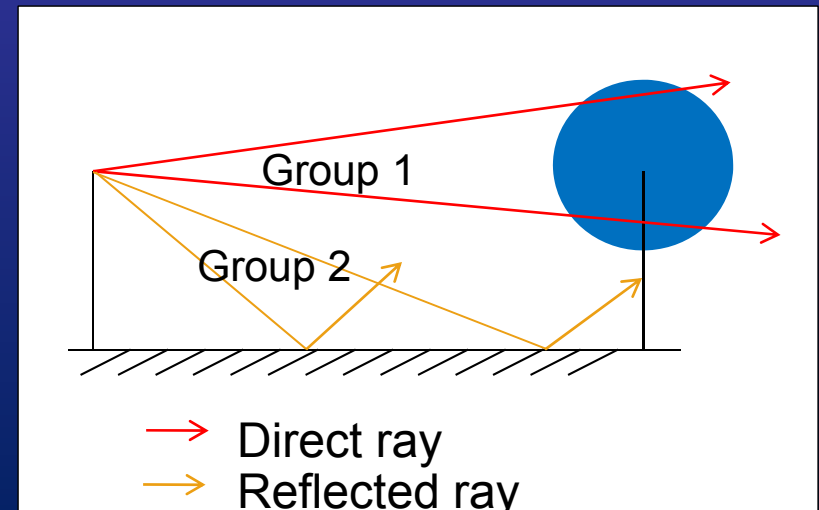
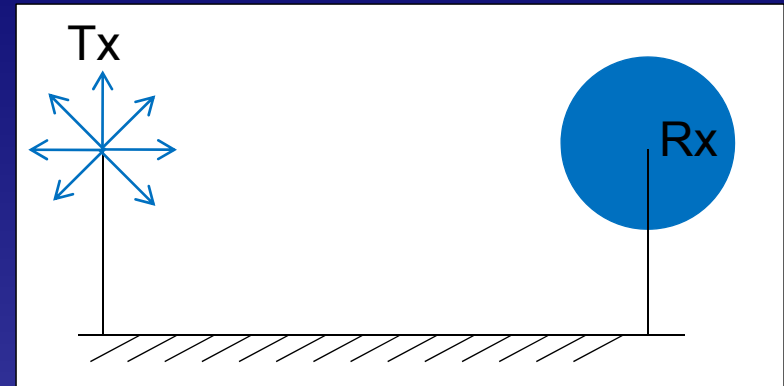
- Computation of the total electric field

- Summation of the electric field contributions of each ray-path



SBR Ray-Tracing – Algorithm

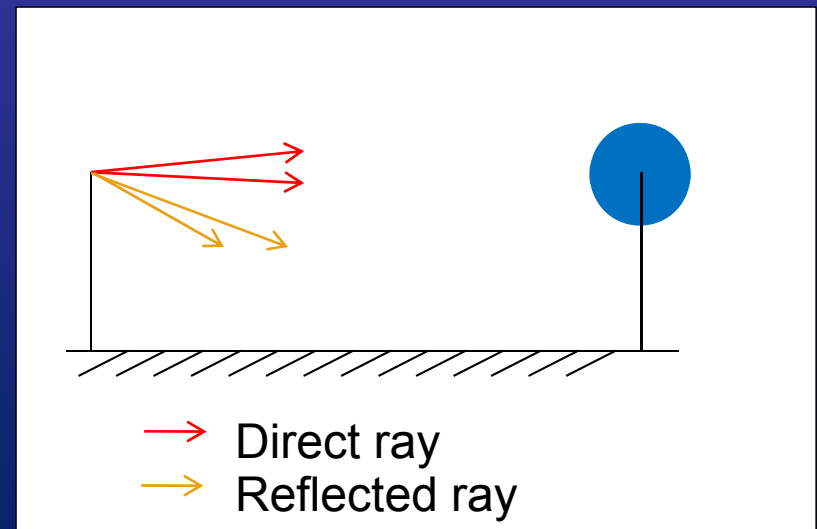
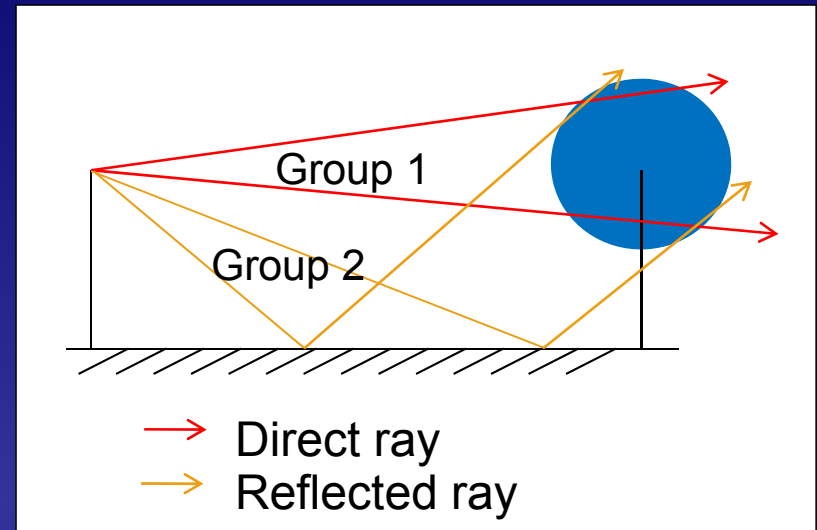
- i. Based on initial angular resolution, create sphere around receiver
- ii. Launch rays with origin at the transmitter at discrete angles throughout space
- iii. For each ray, compute the intersection with all surfaces, find the closest valid one and the reflected ray
- iv. Recursively trace the reflected ray till the termination condition is reached
- v. Group received rays according to their trajectory





SBR Ray-Tracing – Algorithm

- vi. For each group, determine new angular limits
- vii. Reduce angular resolution, sphere size and repeat steps (ii) – (vi)
- viii. With final angular limits, repeat steps (ii) – (iv) and store all relevant electrical properties of objects encountered in environment

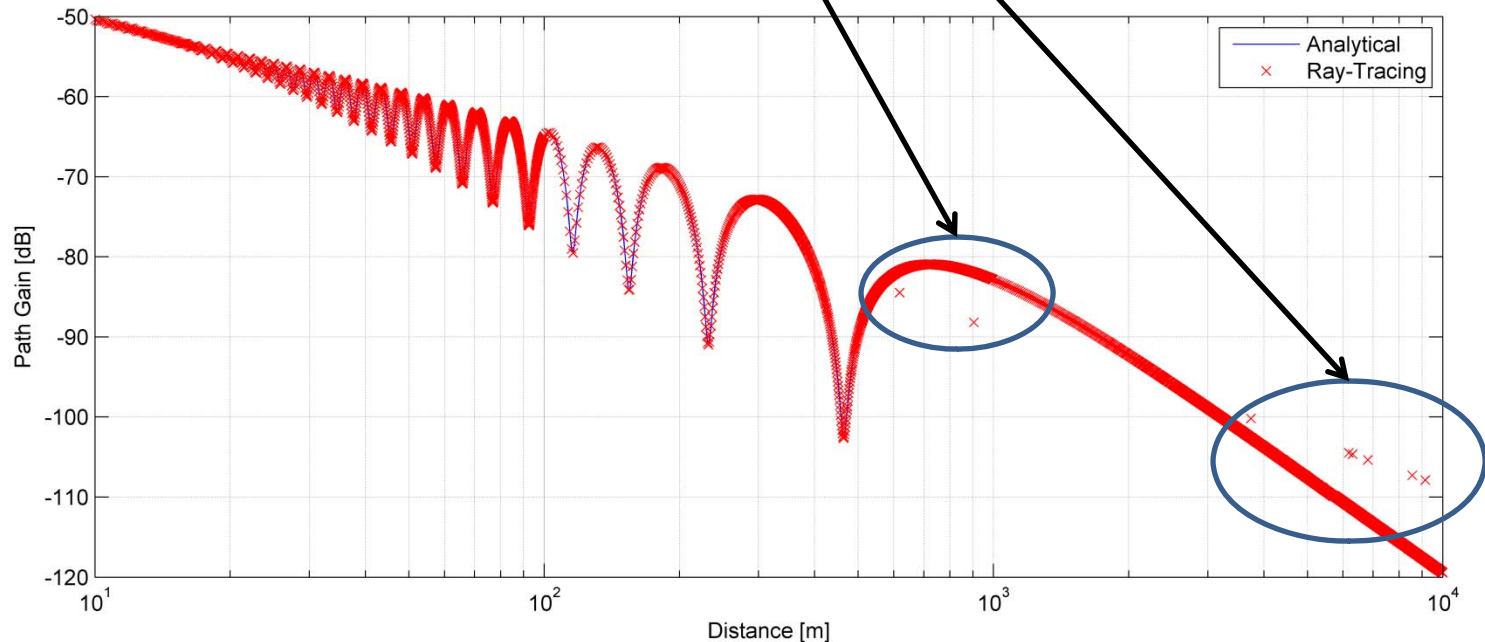




SBR Ray-Tracing – Problems

- Numerical Instability

- For large separation distance ($\sim 1\text{km}$) between TX and RX, random distance points show inaccurate results.
- Contribution due to some reflected paths not accounted.
- Figure shows example of propagation over ground at 5GHz.





IT Ray-Tracing – Algorithm

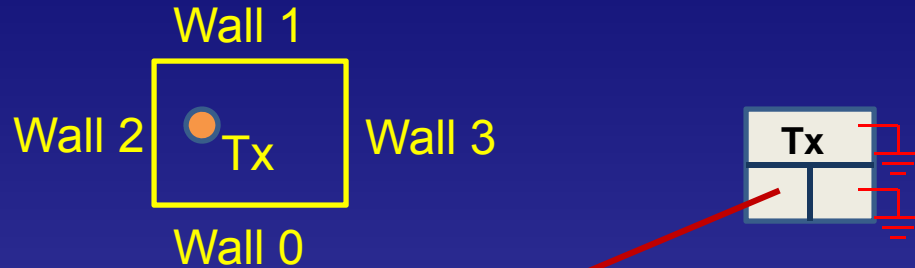
- Step 1: Generate Image Tree



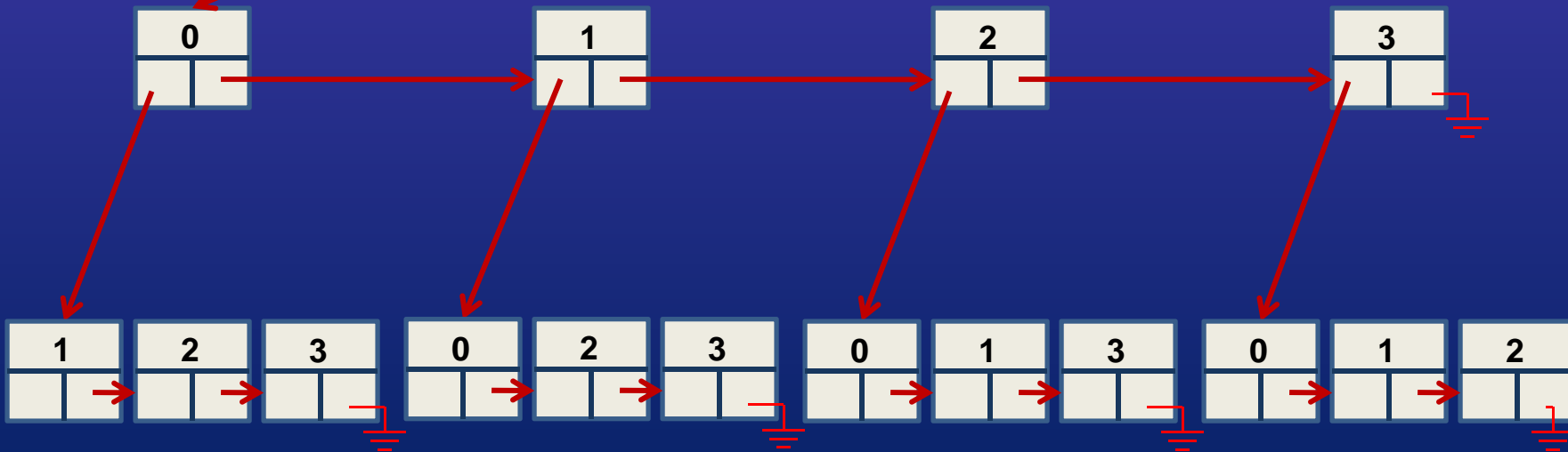


IT Ray-Tracing – Algorithm

- Data Structure for storing image tree



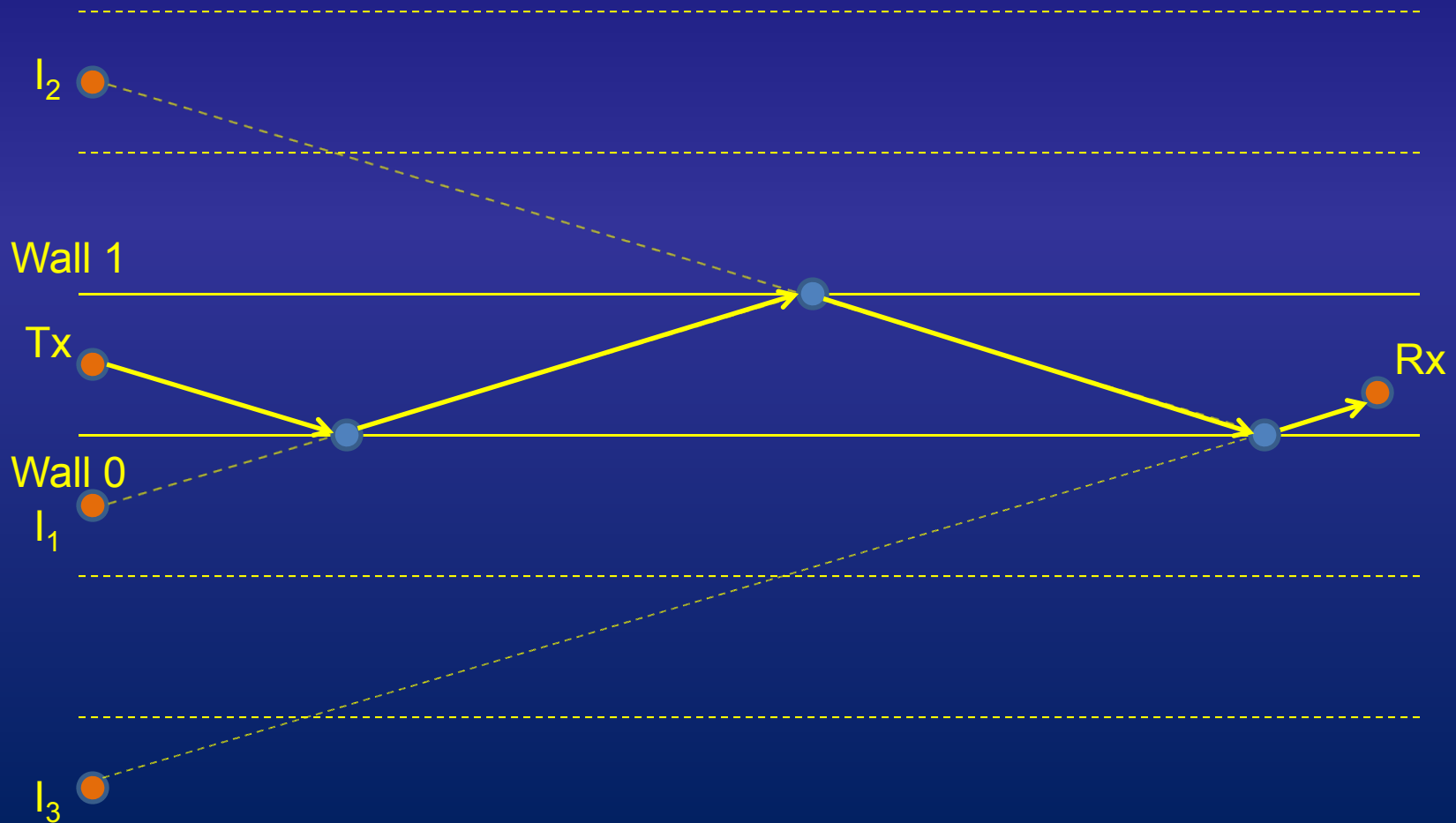
For N planes and up to k reflections, last level of tree has $N(N-1)^{k-1}$ nodes.





IT Ray-Tracing – Algorithm

- Step 2: Determine which nodes represent physical paths by tracing backwards the path for each node





IT Ray-Tracing – Limitations

- **Memory Requirement**

- For a channel with N planes and allowing up to a maximum of k reflections, the i^{th} level of the tree has S_i nodes, where,

$$S_i = N(N - 1)^{i-1}$$

- Therefore total number of nodes, S , in the image tree is given by

$$S = 1 + \sum_{i=1}^k N(N - 1)^{(i-1)} = 1 + \frac{N \left[(N - 1)^k - 1 \right]}{N - 2}$$

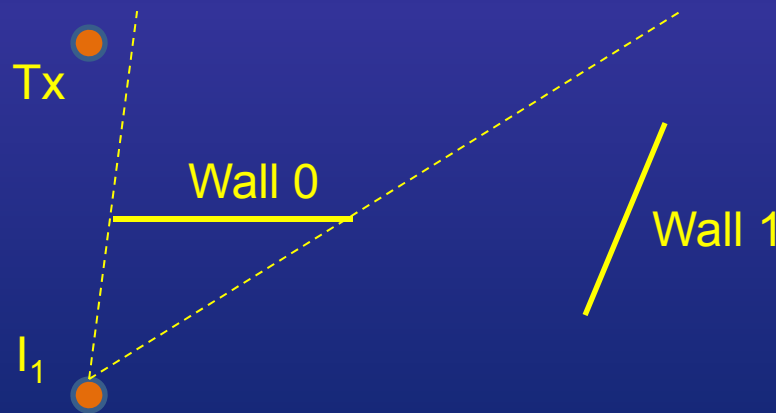
- Total number of nodes grows exponentially as we increase the maximum number of reflections allowed.
- The base of the exponent is dependent on the number of planes.
- Therefore, for practical problems, the image tree can not be stored in memory all at once.
- Generate one node at time along with its hierarchy.



IT Ray-Tracing – Limitations

- Execution Time

- Also depends on the total number of nodes in the image tree since each node represents a potential ray-path that could exist.
- Therefore, to reduce execution time, number of nodes that need to be tested must be reduced.
- Using illumination zones, a reduced image tree is generated.

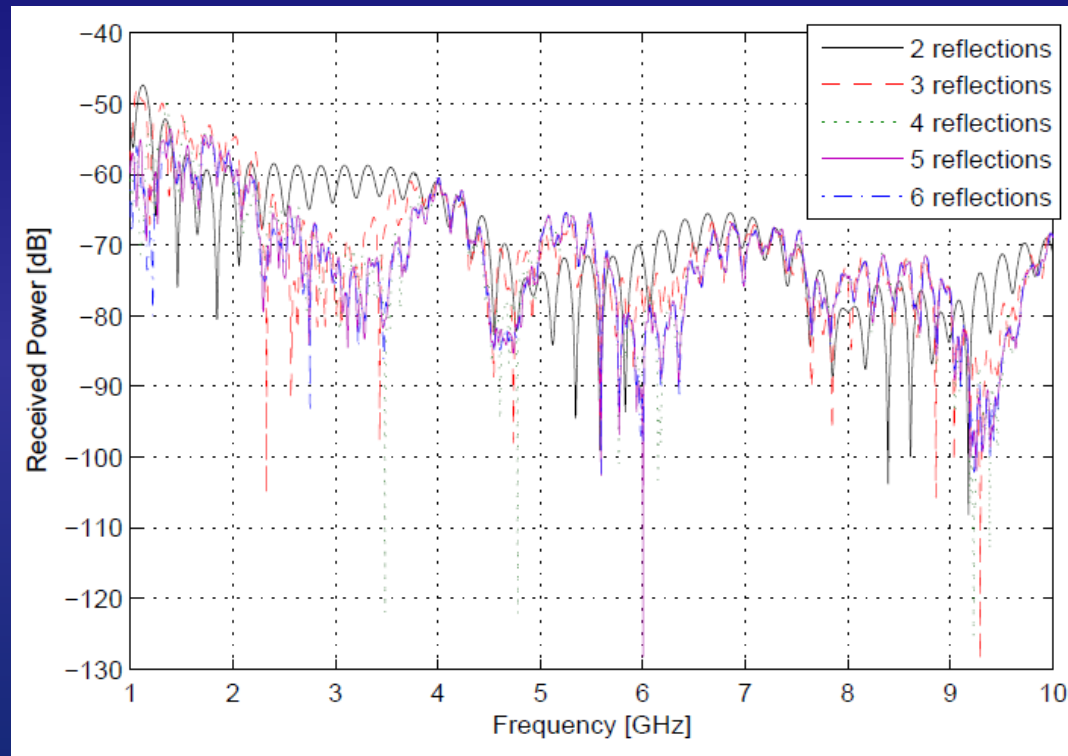


- Sub-tree of image I_1 does not need to include the reflection of I_1 through Wall 1 since it is outside of its illumination zone.



Setting Simulation Parameters

- How is the maximum number of reflections to be used determined?

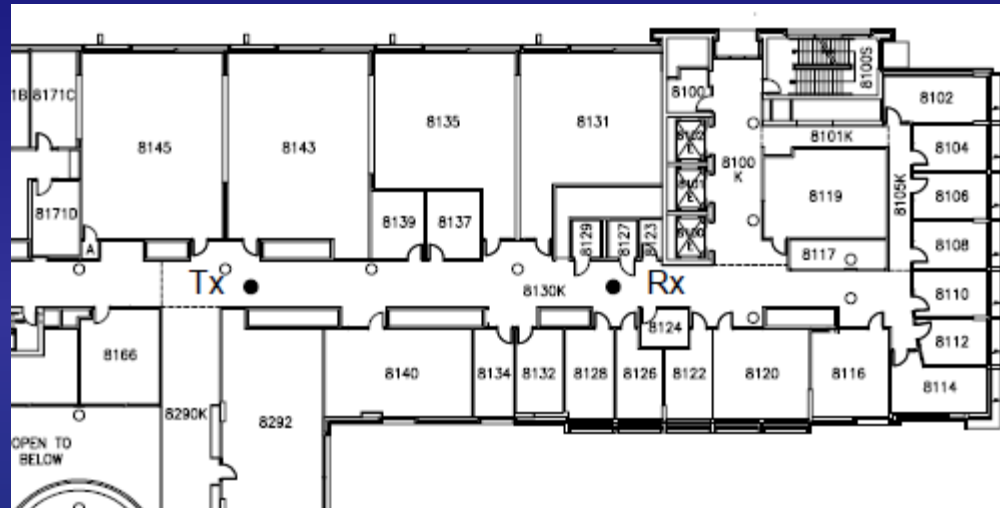


- For curved surfaces that are approximated with planes a similar approach is used.



Experimental Validation

- Measurements (Tony Liang)
 - 8th floor of Bahen in the hallway shown in figure below

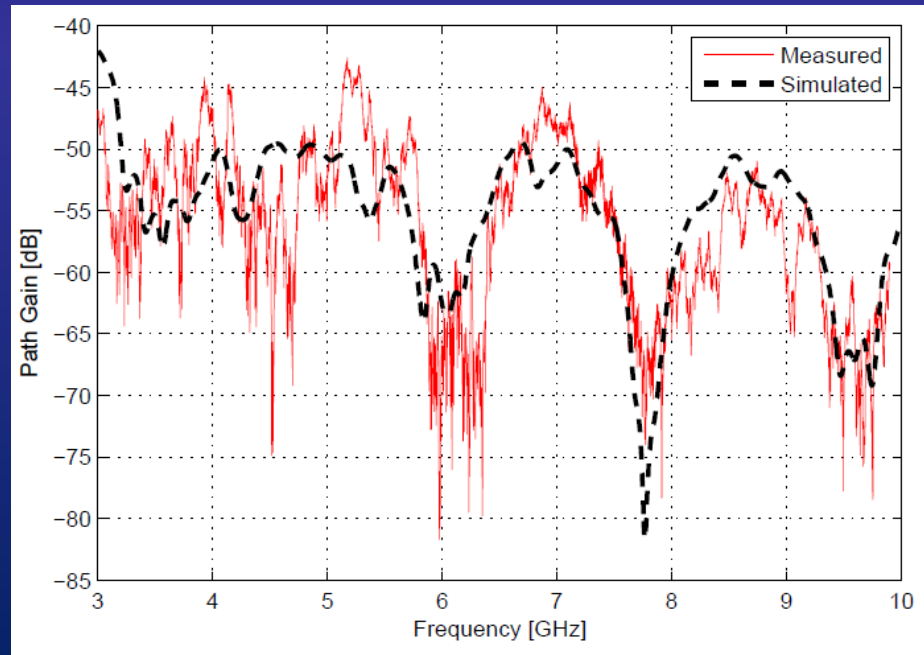


- TX and RX placed 1.28 m and 1.36 m high respectively
- Distance between TX and RX was 22.5m
- Wideband impulse response measure over 3 – 10 GHz
- TX and RX were custom-built balanced antipodal Vivaldi antennas (BAVAs)



Experimental Validation

- Simulation
 - Hallway approximated as a uniform rectangular tunnel
 - Smooth concrete walls assumed, ignoring fine features
 - Dipole antenna pattern is used for TX and RX instead of that of BAVA
 - $\epsilon_r = 5$, $\sigma = 0.001$
- Comparison of measurement vs simulation shown below



- Agreement is good despite approximations

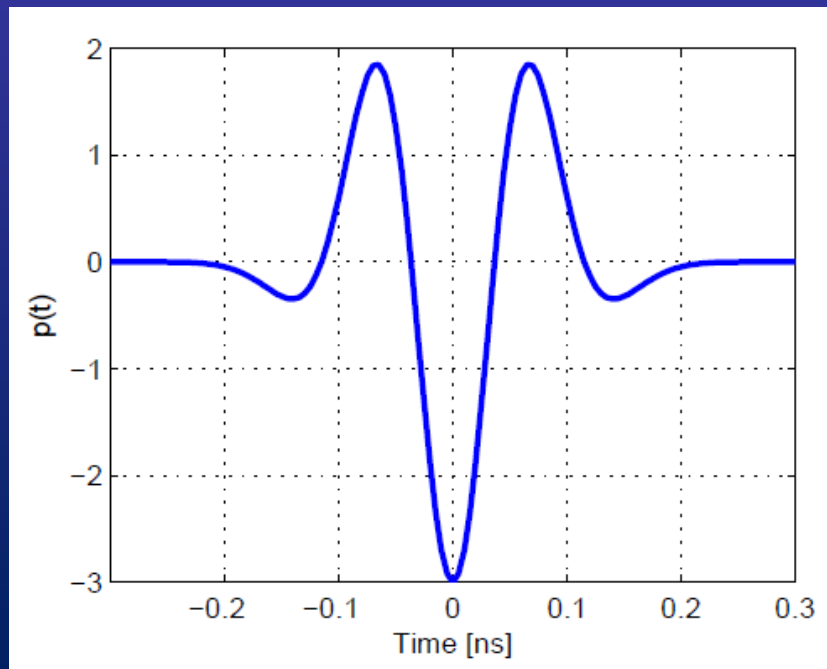


Application – UWB Pulse Propagation

- Fourth-order Gaussian monocycle pulse*, $p(t)$ was used with $\tau_p = 0.175$ ns

$$p(t) = \left(-3 + \frac{24\pi t^2}{\tau_p^2} - \frac{16\pi^2 t^4}{\tau_p^4} \right) e^{-2\pi \left(\frac{t}{\tau_p} \right)^2}$$

- Satisfies the FCC mask for a UWB pulse

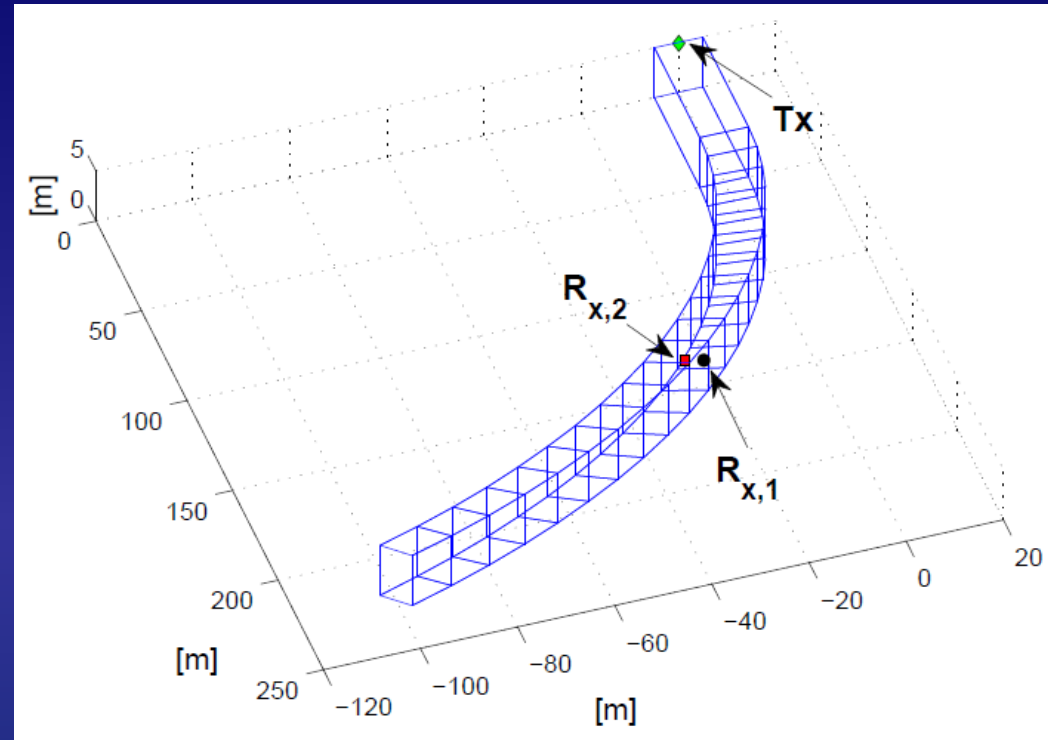


*[Hu et al., "Pulse shapes for ultrawideband communication systems," IEEE Trans. Wireless Commun., vol. 4, no. 4, pp. 1789–1797, Jul. 2005]



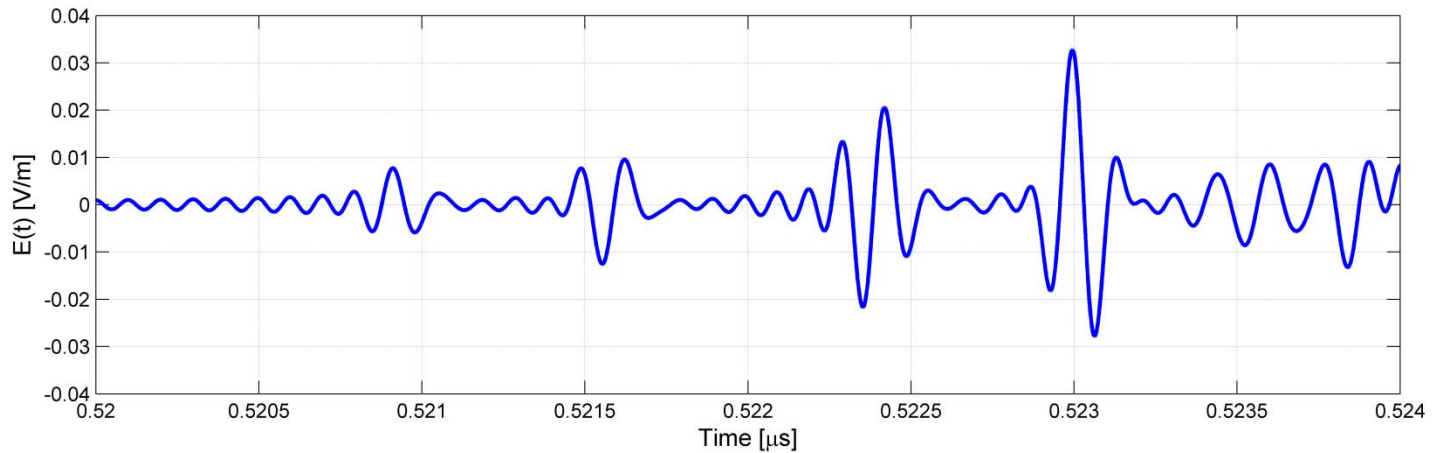
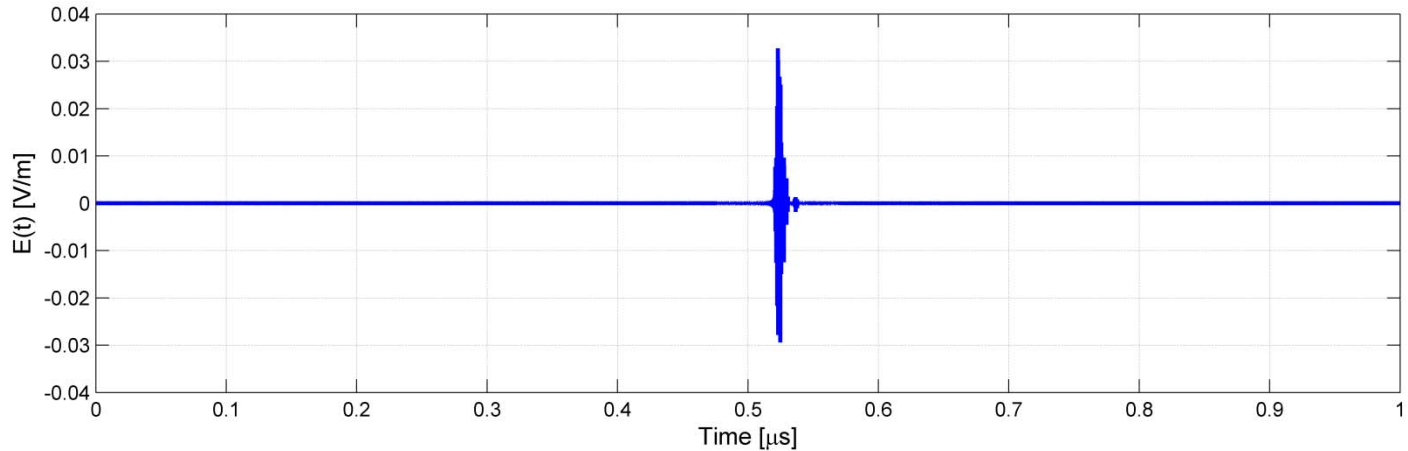
Curved Rectangular Tunnel

- Tx Height = 4.9 m
- $R_{x,1}$ Height = 3 m
- $R_{x,2}$ Height = 3 m
- $Tx - R_{x,1} = 153.79$ m
- $Tx - R_{x,2} = 152.39$ m
- $\epsilon_r = 5$
- $\sigma = 0.001$
- Frequency 1 – 10 GHz
- 10 m wide, 5 m high
- 50 m long straight section
- Followed by 60° circular arc of radius 200 m.
- Each 3° of circular arc is approximated using one rectangular prism.





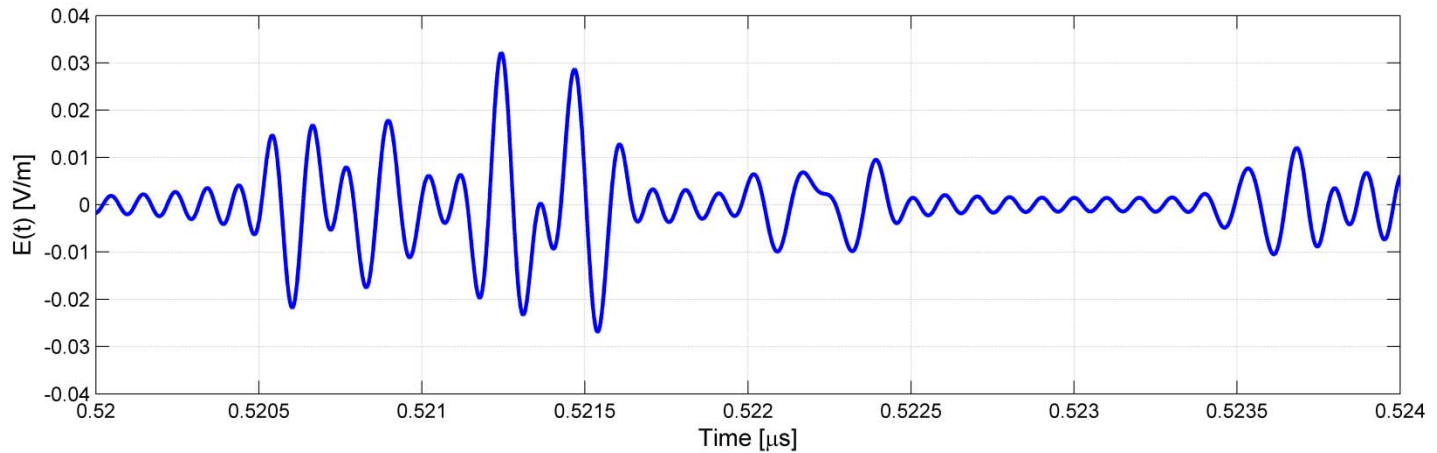
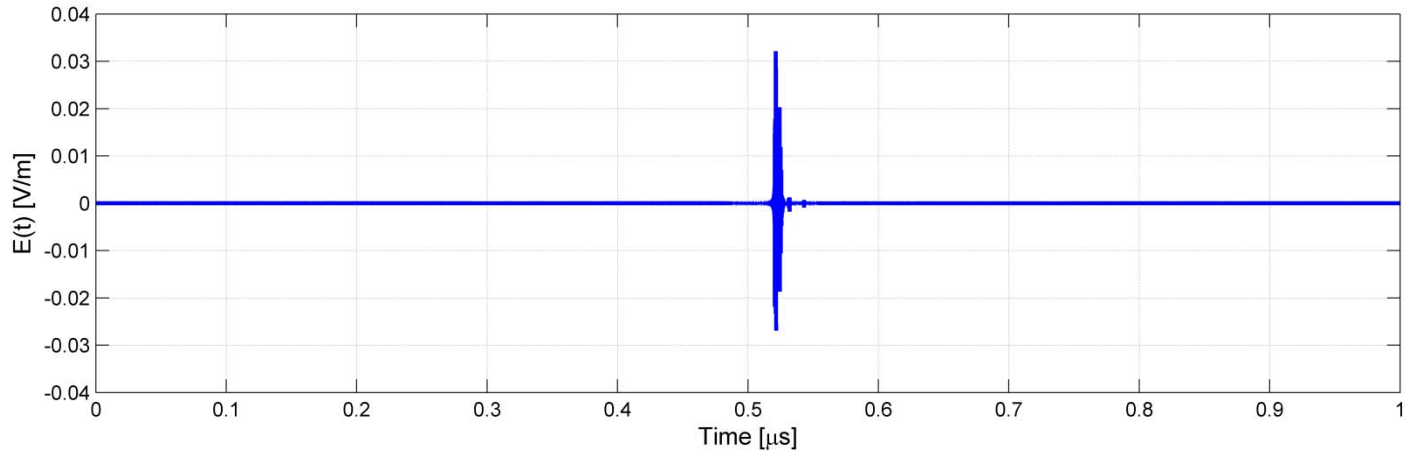
Received signal at $R_{x,1}$



- Distinct multipath components



Received signal at $R_{x,2}$

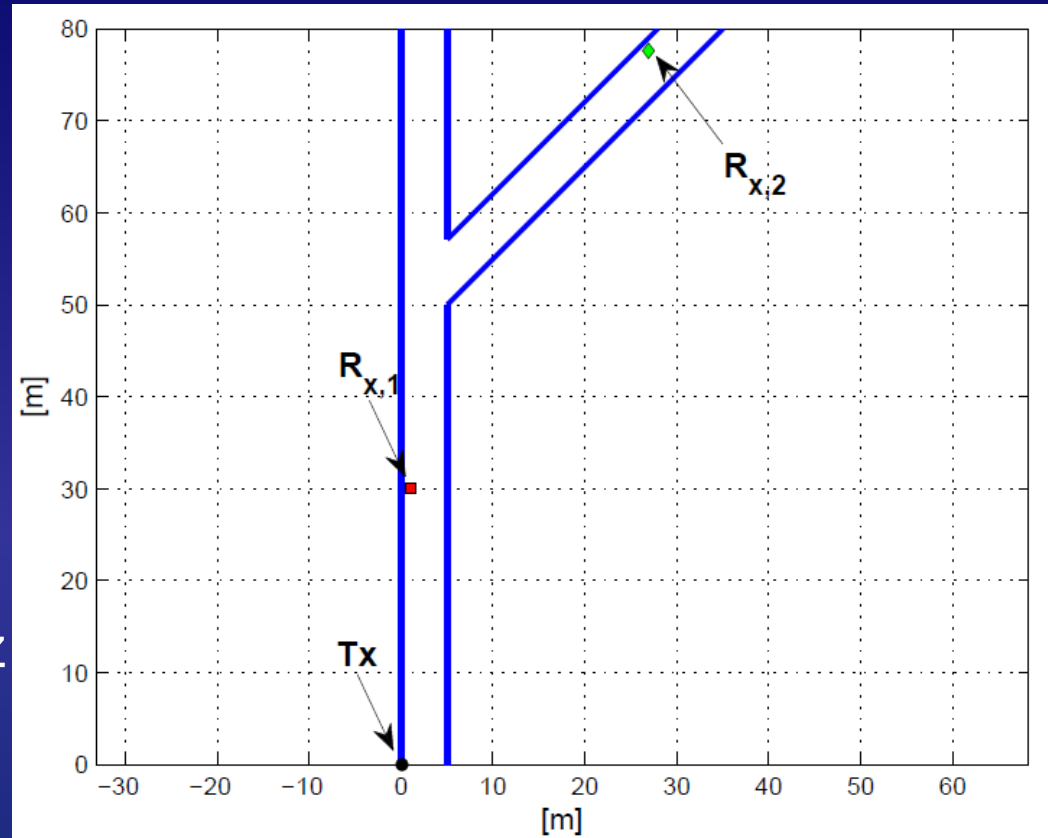


- Multipath components are not distinct



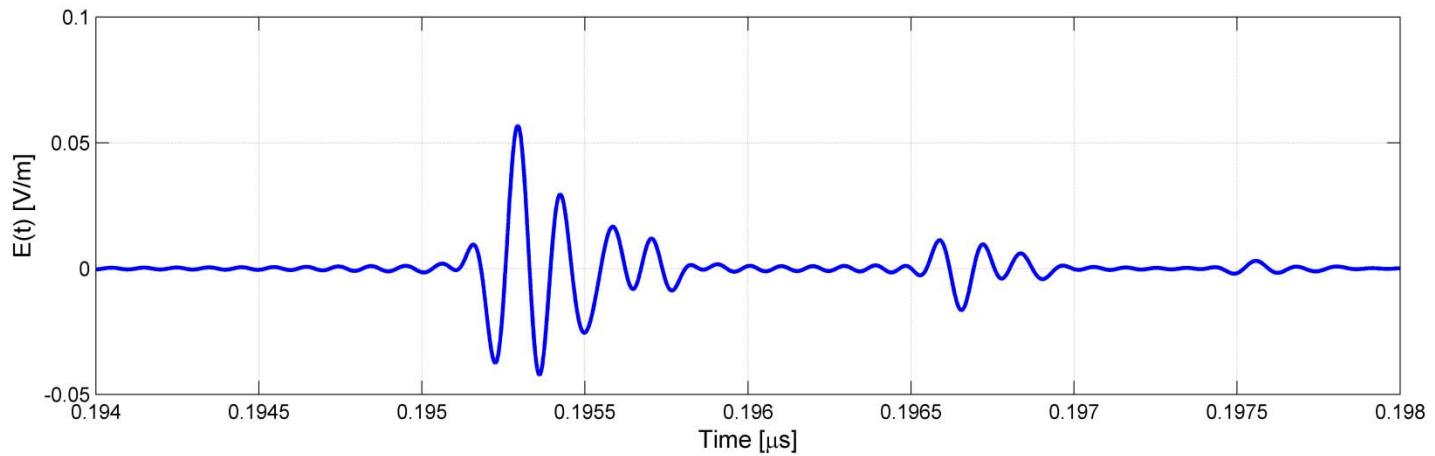
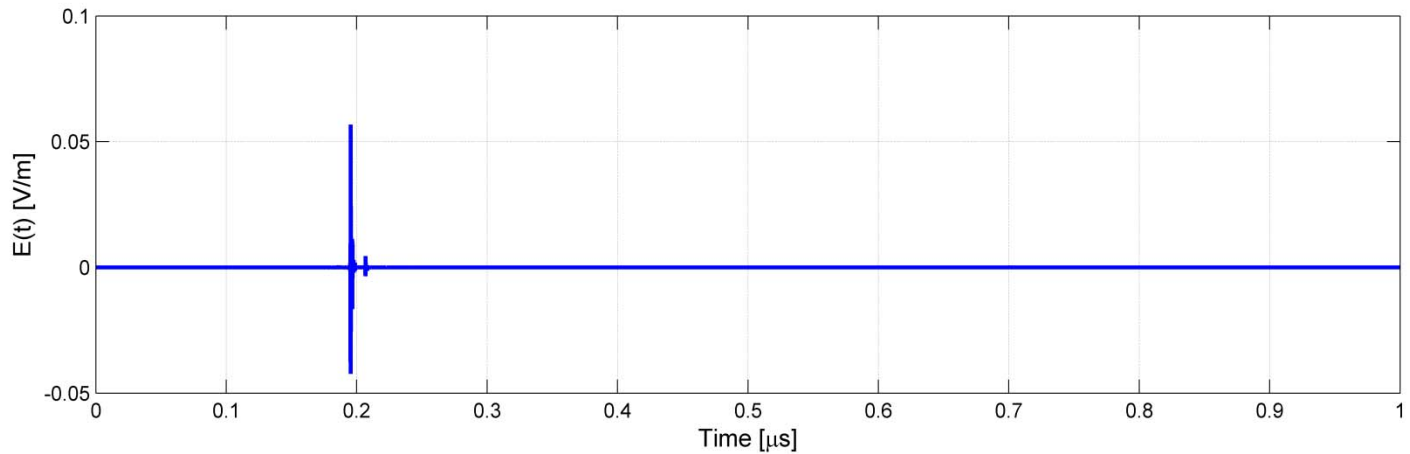
Branched Rectangular Tunnel

- Tx Height = 4 m
- $R_{x,1}$ Height = 3 m
- $R_{x,2}$ Height = 3 m
- Tx - $R_{x,1}$ = 30.03 m
- Tx - $R_{x,2}$ = 82.09 m
- $\epsilon_r = 5$
- $\sigma = 0.001$
- Frequency 1 – 10 GHz
- 5 m wide, 5 m high
- 50 m long straight section, followed by a branched section
- Branch is at a 45° angle to the main section





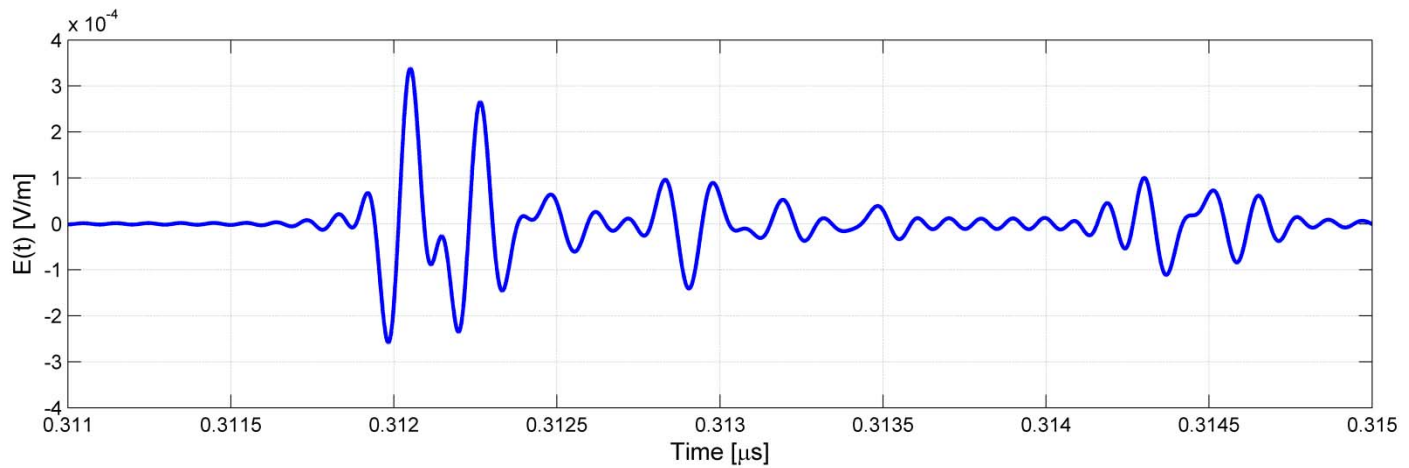
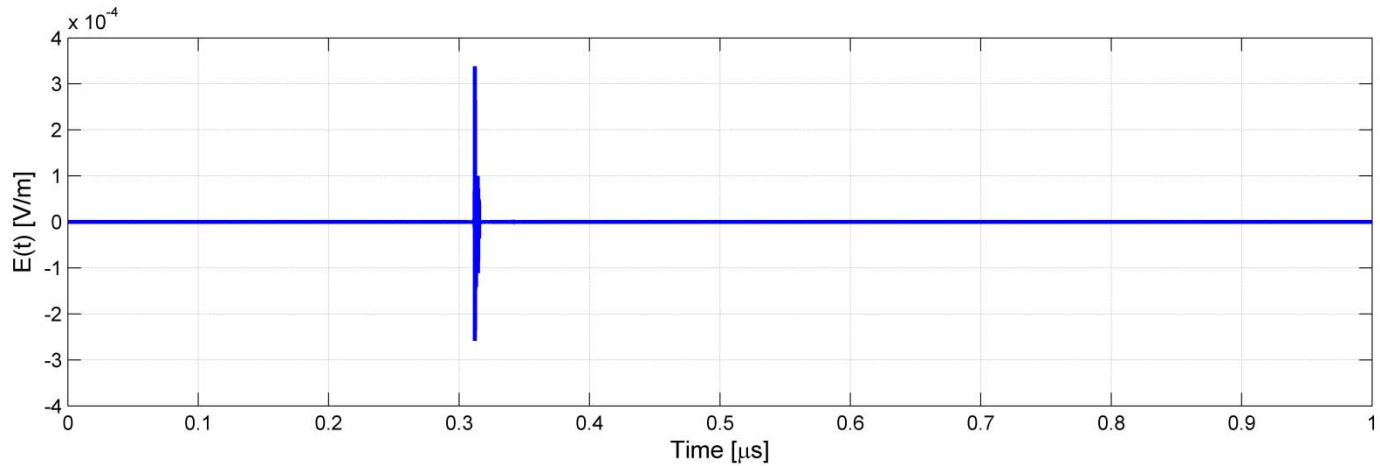
Received signal at $R_{x,1}$



- Multipath components are not distinguishable



Received signal at $R_{x,2}$



- Multipath components are not distinguishable

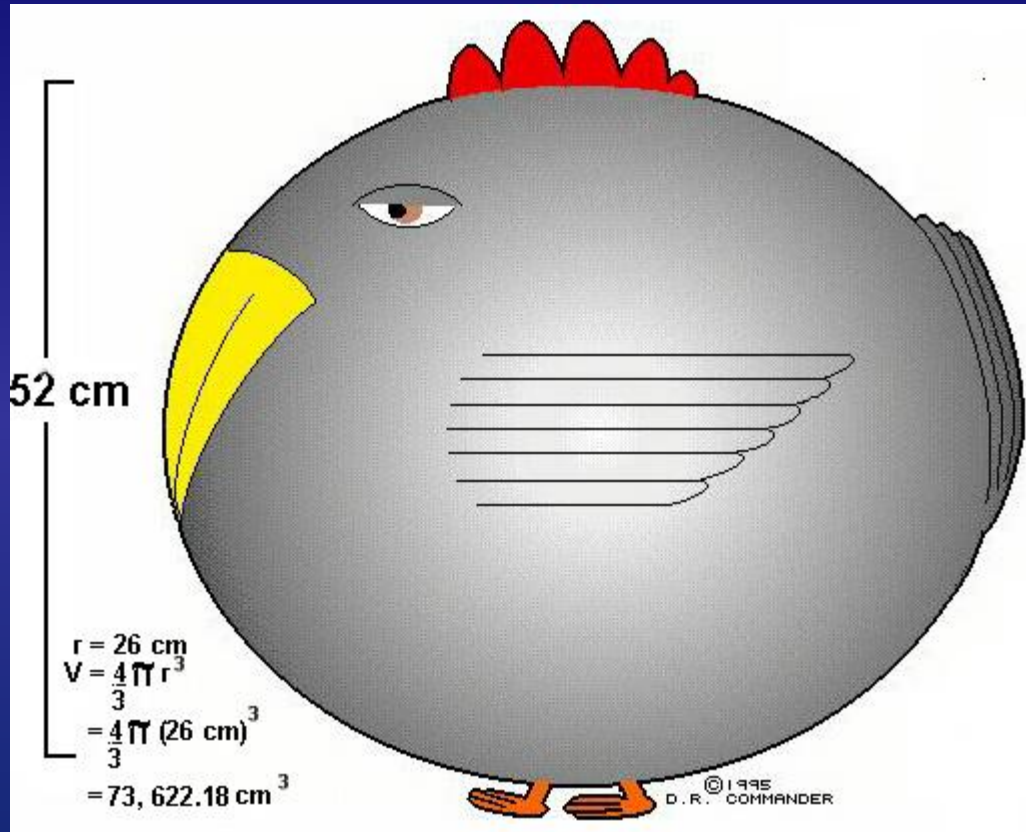


Conclusion

- Ray-Tracing is a useful tool for understanding propagation of UWB signals in complicated environments.
- Reasonably accurate results can be obtained without accounting for fine details.
- Simulation parameters if properly set can optimize accuracy as a function of execution time.
- **Future Work**
 - Validate, Validate, Validate
 - Illumination zones
 - Diffraction
 - Hybrid approach = Ray Tracing + Waveguide Theory



Questions?



Thank you !