Validating Radio Wave Propagation 2-D Ray Tracing Simulation

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***Abstract*—Radio wave propagation phenomena in a dense urban environment can be simulated using publicly available mapping data and 2-D ray tracing techniques when the receivers and transmitters can be found to be near co-planar. This paper outlines and attempts to validate such a simulation model. Validation is presented in the form of experimental results for a set of trials along with a statistical comparison to simulation results. A significant positive correlation between the experimental and simulation results is found and detailed.**

I. Introduction

This paper explores the feasibility and accuracy of modeling multi-path radio wave propagation in a dense urban environment using 2-D Monte Carlo ray tracing and publicly available street mapping data. A propagation model of limited scope is presented that incorporates only those phenomena that are expected to be the most significant sources for reasonably accurate prediction. The software implementation of this model in the form of a 2-D ray tracing engine is described. The design and setup of an experiment conducted in an attempt to validate the results of the model and simulation are outlined. Finally, the results of the experiment are compared with results generated by the simulation.

Specific focus is placed on modeling and simulating the multi-path propagation of monochromatic signals from transmitters in motion to stationary receivers. All transmitters, receivers, and scene geometry are assumed to be co-planar.

II. Scene Model

Urban environments will be modeled using simple planar geometry consisting of points joined by straight line segments. Any curved surfaces or other irregular geometry will be approximated using these primitives. Each line segment represents the impassable outer surface areas of buildings and other structures that make up the propagation boundary conditions. No other structural details, interior or exterior, are accounted for. Geometry is grouped into closed polygons, with each polygon representing a discrete building or structure. Associated with each of these polygon structures is a generic and unit less roughness attribute and the index of refraction for the predominate material the structure exterior is composed of. The roughness attribute has a range of 0.0 to 1.0, with 0.0 representing a very smooth mirror-like surface and 1.0 representing a very rough surface. The degree of roughness is set arbitrarily with respect to the signal wave length being modeled.

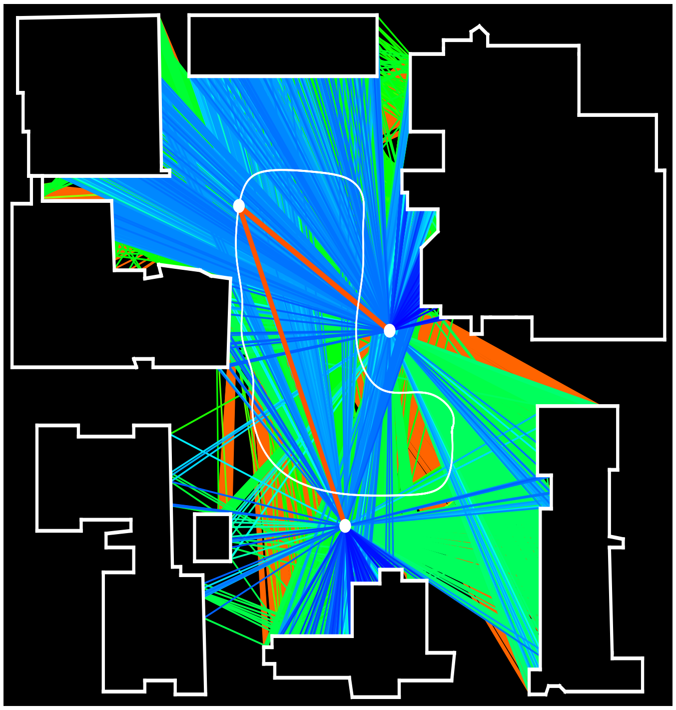

Fig. 1. An example scene as represented by the developed simulation software. This figure depicts a single simulation frame, with the buildings, transmitters, receivers, and transmitter motion path in white, and the signal rays colored by amplitude.

Transmitters and receivers are represented by points. All transmitters and receivers are modeled as isotropic. Each transmitter and receiver has an associated center frequency. Each receiver has an associated bandwidth and resolution, and each transmitter has an associated transmit power. Transmitters can be assigned a path of motion which consists of a set of point and time pairs.

The structural geometry, transmitters, and receivers are combined to make up a scene. A scene has an associated time that determines the position of each transmitter along the transmitter associated paths. An example scene is given in Figure 1 and Figure 2.

III. Propagation Model

The radio wave propagation model focuses on the following phenomena: free-space path losses, specular reflection, diffuse reflection, frequency selective fading, and Doppler effects. The models for these effects are firmly established. Phenomena such as diffraction and through-geometry transmissions are not considered. A detailed description of the model can be found our previous work on the subject [1]. We will only discuss in detail the differences from the model detailed in our previous work and the model used in this work.

Diffuse reflection is modeled by randomly diverting the direction of reflected rays with a uniform distribution around the semicircle centered about the surface normal extending from the point of collision. The power of each ray is then attenuated by the surface assigned bi-directional reflectance distribution function (BRDF) [2][3][4]. In this case, the normalized Blinn-Phong BRDF is used for its energy conserving properties and simplicity of implementation [5]. This BRDF is typically applied to computer graphics rendering, and is not designed to simulate the much lower frequencies examined in this report. An assumption is made that the much larger scale features, when compared to the small scale surface features relevant to visible light wave lengths, produce a similar reflectance distribution for the lower frequency wave lengths of interest here. The BRDF parameters are selected in a frequency independent manner in order to achieve a physically plausible reflectance distribution.

Other BRDFs were also examined, including Phong [6] and several forms of Cook-Torrance [7]. The Phong BRDF is the simplest solution, scattering energy in all directions uniformly, but this type of distribution is not representative of the conditions we are attempting to simulate. Cook-Torrance BRDFs approach the physically based micro-facet techniques. Constructing a physically based and frequency dependent BRDF was explored, but the added complexity necessary to implement these was prohibitive. Physically based radio wave scattering from rough surfaces is covered extensively by Beckmann, Spizzichino, and Oglivy [8][9].

Because the model is limited to two dimensions, many important propagation phenomena will be excluded. Two such important phenomena are ground reflection and over-building diffraction. There are sure to be other ignored effects that would be important contributions to the results, but these effects were a prominent cut-off point when designing the model.

IV. Ray Tracing

Simulation is performed using Monte Carlo ray tracing with the scene and propagation models. This is a well established technique for synthesizing photo realistic images [2][3]. Simulation is performed over time in discrete time steps. Each step is called a frame. The frequency of these steps is called the number of frames per second. For each frame the scene time is updated and a set number of rays are cast in uniformly distributed random directions originating from the current position of each transmitter. Each ray consists of an origin point, a direction vector, a signal frequency, and a power level. When a ray collides with the scene geometry a new ray is cast with the same frequency, a reduced power level, and in a random direction. The power level of the reflected ray is attenuated by the BRDF assigned to the surface at the point of collision. The BRDF is specified by the roughness and index of refraction attributes associated with each polygon structure. These rays are then traced through the scene until they either exit the scene, drop below a set power threshold, or exceed a set number of reflections.

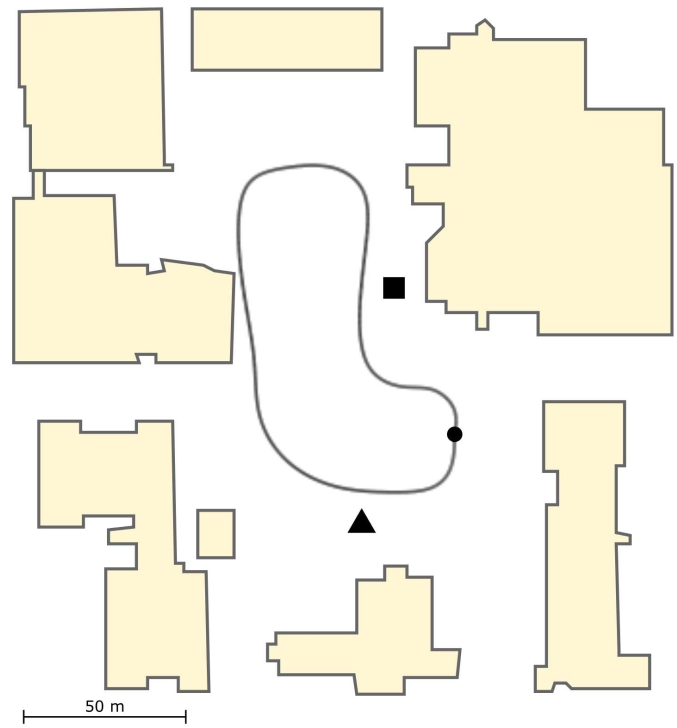

Fig. 2. A map of the experimental setup and one of the TX paths. RX1 is marked by the solid black square, RX2 is marked by the solid black triangle, and the initial and final positon of TX is marked by the solid black circle.

At each ray-surface collision a line-of-sight (LOS) check is performed with each receiver. If a receiver is determined to be in LOS, then an additional ray is cast deterministically to the receiver. Since each receiver is an infinitesimal point, it's not reasonable to expect any rays to ever collide with a receiver randomly. The power of the receiver rays are attenuated by the same BRDF as the randomly reflected rays. The greater the difference of angle between the direction to the receiver and the specular reflection direction the less power-significant the contribution is to the receiver. The sum total of these receiver contributions during each frame make up the received signal data. The received signal data can then be visualized over time in the form of spectrograms and histograms.

A detailed description of the ray tracing algorithm can be found our previous work on the subject [1].

V. Validation

An experiment was designed and conducted in an attempt to validate the model and simulation. Careful consideration was taken to limit the scope of the experiment to that which could be reasonably simulated using the described model. This meant

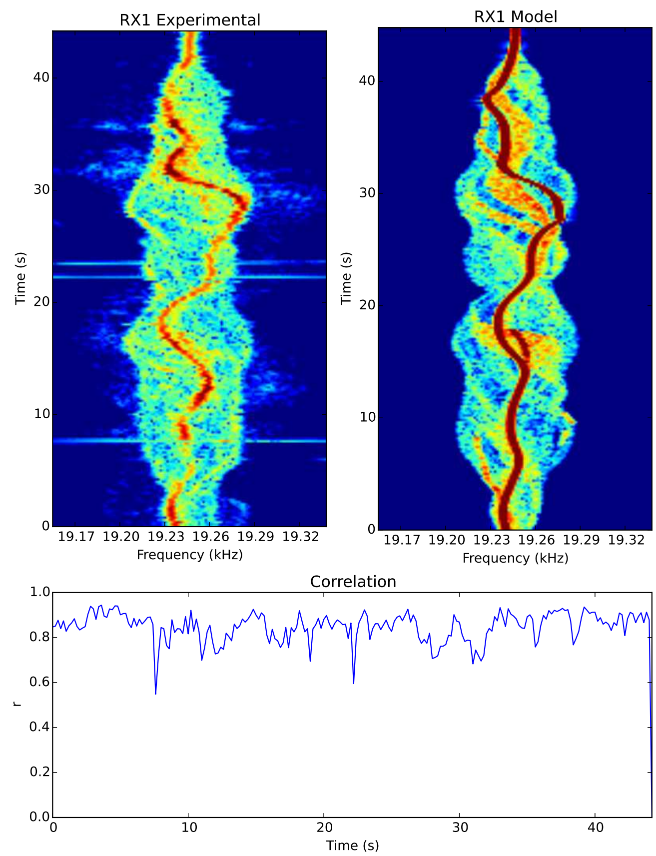

Fig. 3. A side-by-side spectrogram comparison of the data collected at RX1 experimentally and the data for RX1 generated by the simulation. A plot of the Pearson correlation coefficient is given below.

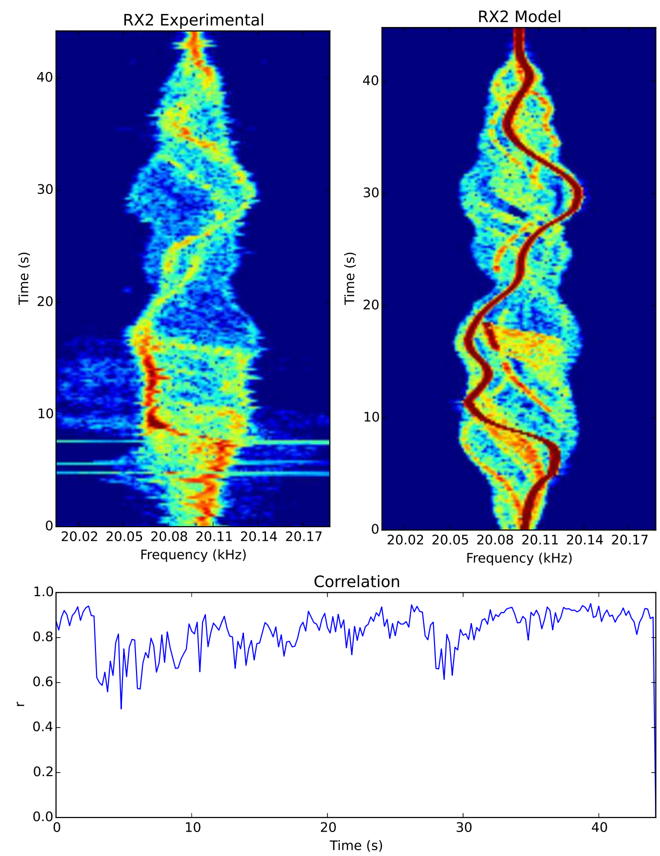

Fig. 4. A side-by-side spectrogram comparison of the data collected at RX2 experimentally and the data for RX2 generated by the simulation. A plot of the Pearson correlation coefficient is given below.

that there needed to be a mobile transmitter with sufficient average velocity for the resulting signal to have a reasonably wide Doppler envelope. It also meant that there needed to be significant and surrounding reflective surface coverage around the transmitter path, with minimal propagation path obstacles in between. The surrounding reflective surface geometry also needed to be highly regular and easily approximated within the scene model. The environment needed to be as static as possible with low occurrences of moving persons or vehicles.

The path velocity requirement meant that the only reasonable choice was to mount the transmitter on an automobile. While running or biking may have provided sufficient velocities, the stability of those platforms when compared with a car or a truck made them less desirable. An automobile transmitter platform meant we needed to be able to perform the experiment such that there was a path that could be legally followed with an automobile. So we needed a road or a parking lot surrounded by buildings with little to no other traffic. Several sites on the campus of The University of Arizona were explored. Ultimately the parking lot in front of the Electrical and Computer Engineering Department building at the University of Arizona was selected as the target site.

A. *Experimental Setup*

Receiver stations would be set up at the carefully considered locations right near the only two available outdoor utility power outlets in the area. The transmitter station would be setup in a small truck with the antennas mounted on the roof. Figure 2 shows a map of the ECE parking lot and all immediately adjacent buildings. Receiver station 1 (RX1) is marked by a solid black square, receiver station 2 (RX2) is marked by a solid black triangle, and the initial position of the transmitter station vehicle (TX) is marked by a solid black circle. The transmitter station vehicle would take laps around the outer road way of the parking lot with different speeds and directions. The path of motion for TX is marked by the solid black line starting and ended at the TX initial position.

Each station consists of a universal software radio peripheral (USRP) and a laptop computer. A frequency of 1.24 GHz was chosen for the transmitter and receivers. This is within the 23 cm amateur radio band, and with an amateur radio license was one of a few legal options that were both ideal experimentally and within the capabilities of our equipment. 23 cm is an ideal option because the target frequency range was between 1 GHz and 2 GHz, which provides a wave length comparable to the irregularities present on the surfaces of most buildings in the area and is also near enough to the bands of the ubiquitous urban radios of cell phones and Wi-Fi enabled devices to provide some partial insight with respect to those technologies.

B. Data Collection Software

The transmitter station software was built with GNU Radio. An unbroken continuous-wave (CW) signal would be transmitted at a 20 kHz offset from the 1.24 GHz center frequency. In addition to the CW signal, it was necessary to transmit identification information regularly according to the amateur radio rules we were operating under. It was also deemed necessary to have a less than 100% duty cycle to avoid heat build-up in the transmitter and to provide any other stations that we might be interfering with a chance to break-in and notify us of the disturbance. The resulting transmitter sequence went as follows: identification in the form of CW Morse code would be transmitted for 5.4 s followed by a 1 s break, immediately after an unbroken CW signal would be transmitted for 60 s followed by a 20 s break. This sequence was repeated without pause for the duration of the experiment. A custom GNU Radio block was written to sample the current GPS location from the USRP installed GPS disciplined oscillator kit (GPSDO) once per second.

The receiver station software consisted of a modified version of a samples capture utility provided with the UHD drivers. The utility was modified to wait for a positive GPS lock status from the GPSDO kit and to sample the current GPS location from the GPSDO kit once per second. It was necessary to sample the GPS data from a separate thread in order to prevent buffer overruns in the main RF sample reading thread. The reason for this is the UHD driver interface to the GPS 'mboard' sensor blocks until a network response with the requested GPS data is received back. The round trip time of this operation is long enough to allow the incoming sample buffer to reach capacity resulting in the loss of sample data.

VI. Results

The collected data post-processing shows a high degree of correlation with the model-simulation generated data. Side-by-side spectrogram comparisons are given in Figure 3 for the RX1 station and Figure 4 for the RX2 station. A plot of the Pearson correlation coefficient is given with each comparison. While most cycles exhibited few discretely visible reflection paths, paths that do show up in the data correlate well with the model both visually and numerically. Additionally many subtleties in the collected data and the model data also correlate well.

The direct path and Doppler envelope also fit well. A plot of the TX velocity is given in Figure 5. The magnitude of the TX velocity plot fits the width of the Doppler envelope and the Doppler-shifted center frequency.

The largest discrepancy seems to be the difference in multipath reflection path strength. This is likely due to the simplistic surface reflection model used by the simulation. The buildings are modeled as highly regular flat surfaces with a uniform

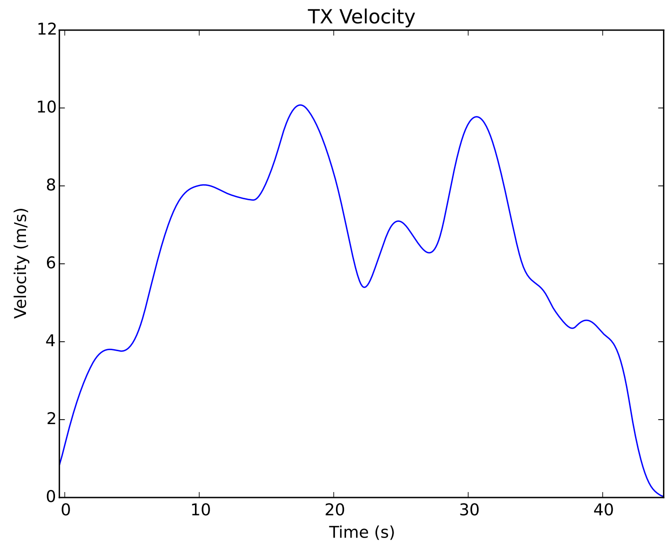

Fig. 5. A plot of the TX station velocity.

roughness attribute, but in reality the building surfaces are highly irregular. A significant portion of the building surfaces were partially obstructed by trees, street lamps, and parked vehicles. These details are all absent from the model.

VII. Conclusion

Despite using a model implementation that was limited to only two dimensions, along with scene geometry based on volunteer supplied mapping data, the experimental data and the model generated data showed a high degree of correlation for most cases examined. The model is simple to implement and computationally cheap. Applicability may be limited in the current form, but it may provide a solid basis for more general models with wider applications.

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