RF Coverage Mapping of Bistatic Radio Links using the Terrain Integrated Rough Earth Model (TIREM)

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***Abstract*—Boasting low cost, complexity, and energy consumption, scatter-based communications has emerged as a prime technology for real time sensing of spectral and environmental behaviors in contentious environments. Successful deployment of scatter networks require RF path loss modeling capability that does not readily exist in commercial tools.**

This work uses the *terrain-integrated rough earth model* (TIREM) – a knife-edge diffraction-based propagation engine – to generate models for bistatic radio links. Using *geographical information services* (GIS) data, RF prediction maps are generated to determine *regions of coverage* that will support link establishment and is uniquely focused on smaller scale environment.

Prediction maps are generated to observe the effects of realistic environments on bistatic link receive power, SNR, and SIR, illuminating the concerns that face these sensor network topologies and making an argument for the use of tools like TIREM to generate quick, accurate information for researchers and designers.

Key Words - **RFID, Bistatic Radio, Propagation, Wireless Sensor Networks**

I. INTRODUCTION

Over the past two decades, scatter based radio has become the ubiquitous technology for low cost, high density, and energy efficient wireless sensing and communication networks. With simplified complexity over traditional radio links, canonical *monostatic* scatter based networks consolidate power hungry hardware and computationally intensive processing to a small number of endpoint transceivers, who interrogate nearby tags/nodes which embed their unique message on impinging waves before scattering the encoded energy back to the same receiver. [1], [2].

There are a handful of applications where transmission and receiving must be performed by physically separated radios. Network topologies where a dedicated transmitter interrogates a tag and the scattered, encoded RF signal is received by an endpoint device at an isolated location are known as a *bistatic* scatter radio configurations, an example of which is depicted in Figure 1.

Bistatic networks are especially suited for scenarios where the transmitter is not under the control of the end user. This is the common situation for spectral sensing in dynamic radio zones, passive radar, and Ambient Scatter Communications (ASC), where a previously transmitted and modulated electromagnetic wave is used as the *carrier* for ulterior messaging done by an unaffiliated user [3], [4], [5].

With the recent increase in research on bistatic scatter radio applications, the rapid generation of reliable path loss models for potential deployment environments is of paramount importance [6]. An accurate path loss map provides designers pertinent information such as anticipated receive signal strength, regions of network coverage, and expected signal to inference ratio (SIR), which when leveraged appropriately facilitates the optimization of future or the diagnosing of currently deployed wireless networks.

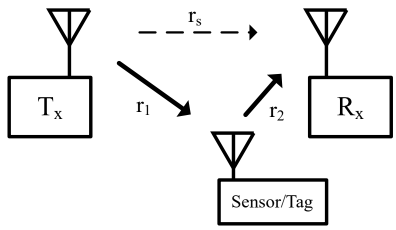

Fig. 1. Example of a simple bistatic scatter link. Energy emitted from the transmitter illuminates the tag. The latter then scatters the energy to an isolated receiver.

The research presented is an exploration in RF prediction mapping for bistatic radio systems via the Terrain Integrated Rough Earth Model (TIREM). TIREM, and its underlying RF assumptions, are discussed as they pertain to this unique application of the tool. Current geographic information systems (GIS) data is fused to create a real-world terrain model for simulation. TIREM protocols are applied to generate path loss prediction maps to determine possible bistatic network configurations based on actual RF illumination, scattering, and receiving device specifications. The resulting plots characterize a 1200 by 600 m area swath in terms of signal to noise and signal to interference ratios.

II. BISTATIC RADIO LINKS

Bistatic radio links, like that shown in Figure 1, feature dedicated transmission and receiving endpoint radios. The scatter based sensor tags, located in the region illuminated by the transmission source, encode and scatter the impinging energy to the be collected and demodulated at an isolated receiver.

The free space propagation loss of a bistatic link can be described, as in Equation (1), by RF wavelength, λ, the gains of the transmitter, tag/node, and receiver, G_T, G_t, and G_R respectively, the transmitter to tag and tag to receiver distances, r_1 and r_2 respectively, and the modulation factor, representing the electrical difference between two switched loads, $M = \frac{1}{4}|\Gamma_a - \Gamma_b|^2$ [2]. This ideal equation assumes an

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omnidirectional tag, where the gain in the direction of each endpoint is equivalent.

$$\frac{P_R}{P_T} = \frac{G_T G_R G_t^2 \lambda^4}{(4\pi)^3 (r_1 r_2)^2} M \tag{1}$$

The signal to noise ratio can be calculated by comparing the receive signal power, P_R, and the noise power which is a function of Boltzmann's constant, k, noise temperature, T_{noise}, and the signal bandwidth, B, as suggested by Equation (2). A combination of hardware sensitivity and signalling properties result in a critical signal to noise ratio, SNR_c, which relates to a physical boundary defining the region of coverage (ROC) for a system. Attempting to operate below SNR_c (beyond the ROC), will result in receiving signals too weak to be discernible in the presence of ambient noise.

$$SNR = \frac{P_R}{P_N} = \frac{P_R}{k_b T_{\text{noise}} B} \tag{2}$$

III. Terrain Integrated Rough Earth Model

A. Overview

The Terrain Integrated Rough Earth Model (TIREM) was the first RF prediction tool to calculate path loss between two points along a spherical body that are separated by irregular terrain. Over fifty years old, this tool has been validated, utilized, and updated with regularity and is now more accessible than ever to non-governmental RF researchers and engineers [7].

TIREM, requiring only a discretized terrain description, calculates path loss for Line of Sight (LOS) and No Line of Sight (NLOS) / Beyond Line of Sight (BLOS) scenarios via a fusion of theoretical and empirical techniques.

This research endeavour, focusing on signals with frequencies around 100 MHz and coverage of an area small enough where topological variations are more affecting than the curvature of the earth's surface, most readily uses free-space propagation, reflection, and knife edge diffraction techniques for calculating path loss. However, TIREM can also include tropospheric scattering, surface wave propagation, and atmospheric absorption effects [8].

B. TIREM Inputs and GIS Data

One advantage of TIREM, is its ability to calculate accurate RF path loss predictions with relatively simple terrain descriptions.

All that is explicitly needed is the RF frequency and a rasterized data set describing the terrain elevation at a discretized distances along the great-circle path between transmitter and receiver. This description, along with other environmental variables such as antenna heights, ground conductivity and permitivity, atmospheric absorption and humidity, are enough for TIREM to 1) classify the channel scenario between transmit and receive endpoints as LOS/NLOS and 2) calculate and combine the effects of the appropriate, dominant propagation mechanisms.

If process above is solved iteratively for each pixel of a topological map, a path loss image can be generated for a fixed RF endpoint.

Most governmental agencies keep updated Geographic Information Systems (GIS) data of their locale's which can include Digital Elevation Maps (DEM), building footprints and heights, and land-use and foliage classifications. This information can be combined using GIS manipulation tools (ArcGIS, QGIS) to generate a rasterized topological map to be passed into TIREM.

C. Bistatic Path Loss Generation

A TIREM-generated coverage map is a rasterized, georeferenced map where the value of each pixel, PR_x, represents the mean isotropic receive power ratio (P_{iR_x}) impinging on that location from a fixed transmitter location.

Those interested in mapping the region of coverage about a fixed endpoint by determining the mean received power at a pixel location, P_R, need simply add receiver gain, $G_R|_{dB}$, to the TIREM calculated P_{iR_x}.

Because the environment can be viewed as an LTI system, reciprocity allows that if the source of the system is located at a given pixel and the fixed end point is actually the receiver unit, the same fraction P_{iR_x} is achieved. Therefore, bistatic signal strength predictions can be generated by overlaying two independent TIREM images.

By adding values to the combined map, such as transmit power, P_T, transmit and receive gain, G_T and G_R, and two times the sensor tag/node gain, $2G_t$, an estimate of the total power at the fixed receiver from a node located at a given pixel if it were illuminated from the fixed transmitter is produced. The calculation, suggested by Equation (3) is quickly realized and achieves a logarithmic version of the link budget equation in Equation (1):

$$\underbrace{PR_B}_{dBm} = \underbrace{P_T}_{dBm} + G_T + PR_{Tx} + 2G_t + G_R + PR_{Rx} \tag{3}$$

D. Considerations

TIREM, when performing a path loss calculation between two points, takes in to consideration only the terrain profile *between* the end points along the immediate path between them.

This illuminates two specific TIREM assumptions in need of additional consideration:

First, TIREM assumes that any obstruction encountered along this two-dimensional slice extends infinitely in the lateral directions and is a true 'Knife Edge' for sake of calculation. No energy is permitted to "wrap around" the obstruction. Second, TIREM does not regard signal contributions that do not come from along this two dimensional cut, such as nearby reflecting surfaces or structures "further beyond" the pixel in question. Thus, there will be a tendency to underestimate the total signal strength in deeply shadowed microcellular regions.

These two assumptions generate the most pessimistic path loss estimates for situations like those suggested in this work, always erring on the side of discarding other means of directing RF energy to the receiver location. Researchers and designers

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using these maps can therefore expect better performance than that immediately depicted, treating these bistatic maps as a lower-bound on potential receive power.

IV. Ambient Scatter Bistatic Region of Coverage Predictions

This research aims to characterize the campus of Georgia Tech in Atlanta, GA and determine its suitability to host bistatic scatter network systems, illuminated by the college FM radio broadcast tower.

A. Inputs and Terrain Data

TIREM accepts a number of user defined variables which describe the electric properties of air and soil to be modeled along with the irregular terrain profile. The values supplied for this work, listed in Table I, were selected as fair approximations of typical weather and ground conditions of the region [9], [10].

TABLE I
Earth and Atmospheric Simulation Inputs.

TIREM Parameters	
T_x Height	83 [m]
R_x Height	1.8 [m]
Polarization	H
σ_{ground}	2 [S/m]
μ_{ground}	25 [F/m]
Refractivity	301
Humidity	98 [g/m^3]

The specific RF parameters related to the transmitter, the sensor tag, and the receiver are listed in Table II and correspond with the real-world specifications of the on-campus college radio station, a typical omnidirectional, dipole-styled scatterer, and a USRP-friendly dipole antenna, respectively. Additionally, an estimate for noise temperature of 1000 Kelvin was used throughout.

TABLE II
RF Parameters for Simulated Devices and Environment.

RF Parameters	
f_c	91.1 [MHz]
P_T	19.716 [kW]
G_T	9.2 [dBi]
G_R	3 [dBi]
G_t	2.15 [dBi]
T_{noise}	1000 K

Where traditional TIREM users might apply a "blanket" endpoint clutter loss term to certain pixel clusters to represent cities, this work is particularly curious of the effects of terrain *and* specific buildings on RF performance.

Using QGIS, an open source GIS data manipulation program, a map of Georgia Tech's campus was created by fusing both georeferenced terrain and building data. A rasterized version of the underlying terrain profile is overlaid and combined with the building structures modeled both in location and height. The resulting elevation map, depicted in Figure 2, is a grid of heights with respect to sea level with 5m x 5m resolution.

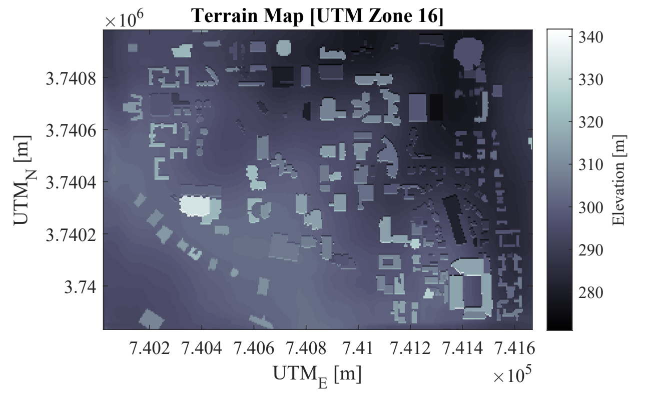

Fig. 2. Elevation map of Georgia Tech's campus. Includes terrain and building footprint and height data.

B. TIREM Path Loss and Bistatic Regions of Coverage

Supplying the TIREM engine with the terrain map and associated parameters, it creates a path loss model as aforementioned and with great speed, generating a 55,000 pixel map in 27 seconds, like those in Figure 3. TIREM's speed make it a powerful candidate for rapid simulation campaigns to determine ideal end point locations.

TIREM foregoes ray-tracing and phase based calculations, rendering it unable to characterize complex multi-path behaviors, but it is still well noted for its accuracy, easy alteration/correction by empirical loss factors, and its low time and computational cost [6].

Figure 3.a depicts the expected isotropic power received from the Georgia Tech college radio station. This is a high power, high elevation transmitter, and provides a great deal of coverage. Figure 3.b depicts the behavior of a USRP type receiver located on the top of the college of Electrical and Computer Engineering building on campus.

To make the bistatic coverage map, the T_x and R_x plots are overlain and added together and result in Figure 4, where each pixel represents the power received at the receiver if a scatter located at the pixel position was illuminated by the FM radio tower.

Perhaps of greater interest to system designers is casting a map like this in terms of SNR, as provided by Figure 5. Using Equation (2) and normalizing to a signal of 1 kHz bandwidth, a set of contours is generated about the map to show which regions are suitable for different signalling applications.

Both SNR_c contours overlain on Figure 5 assume that 10 dB is needed for using binary phase shift key (BPSK) signalling without additional processing gain and a 15 dB small scale fading margin for a total of 25 dB.

The green contour and the space it encloses, would allow a user to operate with a signal bandwidth of 100 kHz and still meet its necessary SNR_c. One could stream low quality video data within this region. If lower data rates are permissible, as is usually the case with simplistic environmental sensing, the region of coverage becomes much larger. For example, if only

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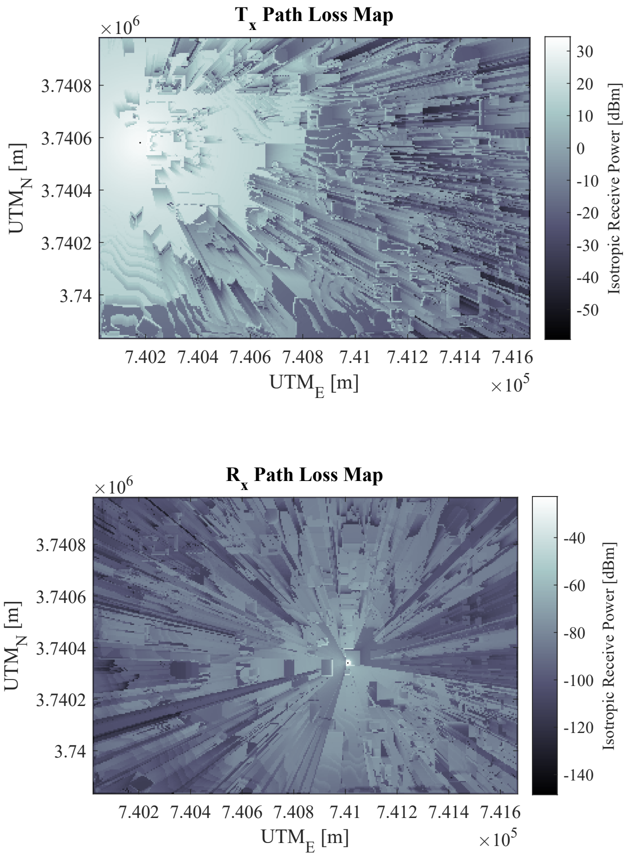

(b) TIREM prediction map for a USRP N200 unit stationed atop the Van Leer building for electrical engineering.

Fig. 3. TIREM RF prediction maps of the expected isotropic receive power ger

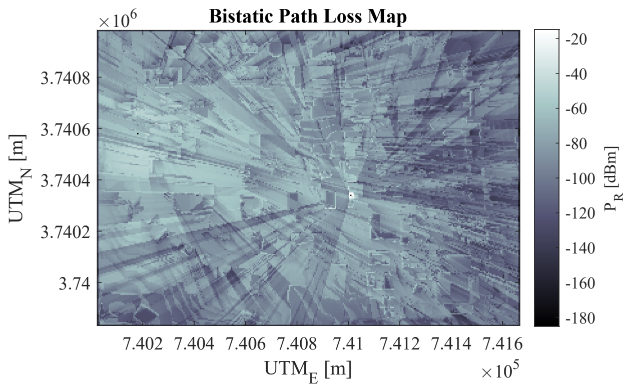

Fig. 4. Bistatic link RF prediction map. Each pixel represents the mean power received should a tag be placed there.

500 Hz is required, then a user could operate anywhere within the red contour on the SNR map.

With this type of treatment, an RF prediction map with contouring is of immediate value to system designers before deployment, allowing them to clearly note the boundaries of their coverage. Furthermore, the designer can generate a single

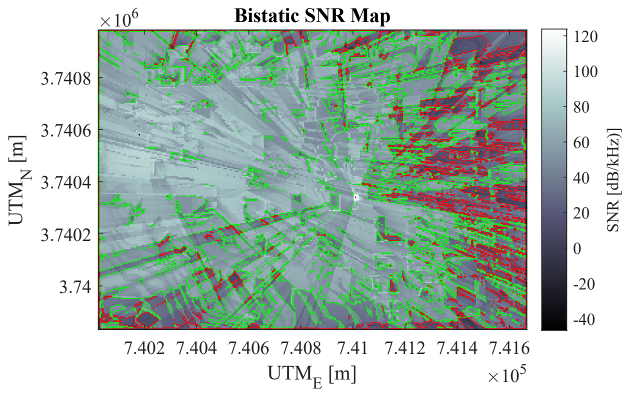

Fig. 5. Relative achievable SNR of the example bisatic link. The green and red contours correspond with the regions permitting 100 kHz and 500 Hz signal bandwidths, respectively.

bistatic map of this kind in roughly a minute, allowing for quick comparisons to try to maximize the regions enclosed by the critical contours.

C. Primary User Interference

Some bistatic radio applications have a unique interference phenomena called Primary User Interference (PUI) which is the interference caused by the illumination source itself, being inherently in-band and much more powerful than the sensor's signal.

In the field of Ambient Scatter Communications, where the PUI is not only strong but of non-negligible bandwidth, it is beginning to be recognized that PUI is the foremost reason for fierce range restriction of measured systems [5].

A canonical, free space description can be derived for SIR due to PUI as Equation (4), which assumes the tag is omnidirectional, the receiver gain is the same for the primary user and the scatter node and the receiver is separated from the illumination source by r_s.

$$SIR_{PUI} = \frac{P_R}{P_{PUI}} = 10\log_{10}\left(\frac{r_s^2}{r_1^2 r_2^2} \cdot \frac{G_t^2\lambda^2}{(4\pi)^2}\right) \tag{4}$$

A TIREM prediction of logarithmic PUI is easily gleaned from the two independent simulations using Equation (5), a much more realistic value than the free-space approximation. Subtracting the PUI value from the bistatic plot, results in a map like Figure 6 which each pixel represents the power differential between the intended bistatic message and the primary user.

$$\underbrace{PUI}_{dBm} = \underbrace{\text{EIRP}_T}_{dBm} + PR_{T_x}([\text{Long,Lat}]_{R_x}) + G_R \tag{5}$$

The contour in Figure 6 is placed at -60dB, a fairly substantial value. It becomes immediately apparent that SIR_{PUI} is much more stringent an operational requirement than traditional SNR metrics. To successfully operate using this communications regime, all tools at the designers hands must be applied to make sense of their signal in the presence of a *much* larger

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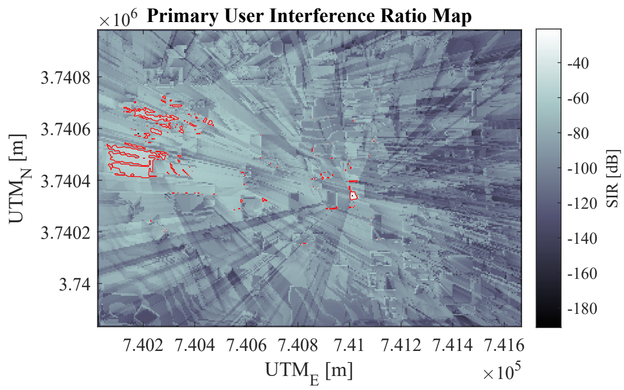
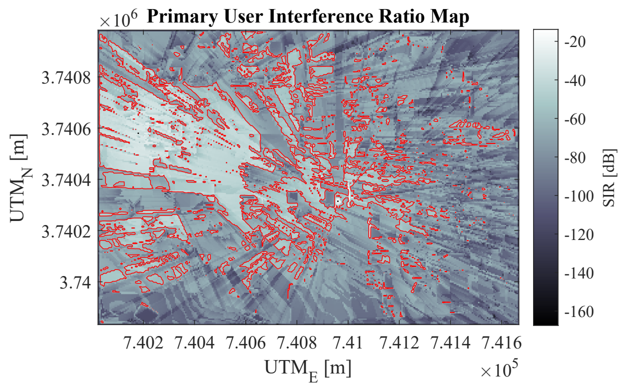


(a) SIR region of coverage caused by PUI.



(b) SIR region of coverage caused by PUI. Transmit to Receive is NLOS.

Fig. 6. A map of PUI created SIR. Regions within the red contour have an SIR greater than -60 dB.

interferer, such as nulling arrays, signal processing methods, and RF/analog filtering stages.

One simple choice could be to select a location where the receiver is better isolated from the radiation of the primary user but still unobstructed from its scatterers. Figure 6.a shows the regions where an ASC system could function if the receiver was still atop a building where Figure 6.b shows how much larger an area of successful operation would be by moving the receiver to the ground in a shadow of neighboring building.

V. Conclusions and Future Work

This research focuses on implementing the long used path loss modeling tool TIREM to determine the suitability of small, complex environments for the successful deployment of bistatic scatter sensor networks. Discussion of bistatic link properties, such as link budgets and primary user interference is combined with an overview of the TIREM path loss generation process.

The work outlines how to quickly generate bistatic path loss models using typical outputs from the trusted path loss modeling tool. An example set of predictions are made for the college campus of Georgia Tech, using GIS data and specified RF system parameters. The resulting images are scrutinized to determine regions of coverage, where successful links might be established, in terms of SNR and SIR metrics.

The authors of this work, particularly interested in the field of Ambient Scatter Communications, are planning a future measurement campaign to compare to these plots and expect that these quick path loss simulations will aid in rapid prototyping of future networks and establishing guidelines in the emerging field.

VI. Acknowledgements

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