Enhanced RF Modeling Accuracy Using Simple Minimum Mean-Squared Error Correction Factors

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***Abstract*—This work proposes a quick, accurate means to generate correction factors for established propagation models such as the terrain-integrated rough earth model (TIREM). Minimum Mean-Squared Error (MMSE) techniques are applied, extending the applicability of this already-accurate and flexible propagation model and improving the standard deviation error between measurement and predicted by as much as 6.9 dB in some regions of a signal-strength measurement campaign at the University of Utah campus.**

Key Words - **Digital Spectrum Twin, Path Loss, Propagation, Wireless Sensor Networks**

I. Introduction

A *Digital Spectrum Twin* (DST) – a virtual representation of current and historical RF spectrum usage in a geographic area – could revolutionize next-generation spectrum management, but only if fast, accurate propagation models can supplement and update the DST wherever measurements are not available (i.e. most places) [1], [2]. This work demonstrates how a well-established, reliable, accurate propagation model can be further improved by fast, supplemental corrective modeling elements to achieve a more accurate, site-tuned model capable of maintaining a DST. Specifically, non-line-of site correction factors are generated and applied to the extremely versatile *Terrain Integrated Rough Earth Model* (TIREM) in order to extend its applicability to shorter-range and microcellular-style radio links.

Measurement data is taken from a college campus between a stationary transmit radio and three bus-mounted mobile receivers. The received signal strength measurements are compared to a TIREM-generated prediction map of the same region. Using minimum mean-squared error (MMSE) techniques, correction factors are generated which reduce the standard deviation of error by as much as 6.9 dB in certain data sets.

This improvement achieves two immediate gains. First, by arriving at a generalized, more accurate TIREM-based model that helps produce propagation maps with increased reliability and also by demonstrating how a simple, intelligent propagation model can tune its own parameters with automated, real-time measurements. This tuning allows the signal strength maps stored in a DST to be updated, adjusted to the environment without significant manual intervention.

TIREM was chosen as a base model for performing this work because it executes quickly, incorporates readily available site-specific terrain information, applies over many octaves of frequency, has been verified exhaustively over the decades, and has relatively low standard deviation error between measurement and prediction. Based on the Longley-Rice Irregular Terrain Model (ITM) developed in the 1960s [3], TIREM uses knife-edge diffraction to estimate losses from 1 MHz - 1 THz and for transmitter-receiver separation distances of up to 30 km [4].

A known weakness of the almost-universal TIREM model is its close-in performance for sub-kilometer transmitter-receiver separation distances; in this region, TIREM's knife-edge diffraction-based modeling engine tends to under-predict received signal strength, assuming diffraction losses for shadowed receivers are acute and discounting the additional power contributed by multipath. To correct this, a non-line-of-site adjustment that selectively adds power in shadowed, close-in regions is proposed and evaluated, thereby extending the utility of TIREM beyond its original range of operation. This method suggests a general non-line-of-sight path loss correction factor between -18.4 and -25.3 dB could be applied to the heavily shadowed, close-in regions using a minimum mean-squared error optimization [5].

II. Terrain Integrated Rough Earth Model

A. Overview

TIREM is a proven RF prediction tool which calculates path loss between two points separated by an irregular terrain [4]. TIREM is a long-running industry and defense standard for this purpose, and has been regularly validated, updated, and employed in the research, design, and diagnostics of modern radio links.

A large part of TIREM's appeal are its speed, producing accurate, wide area signal strength maps in a matter of seconds on a modern computing platform. TIREM only requires a simple, discrete terrain map between two antennas of varied heights and some basic RF and environmental parameters.

Digital elevation maps of a variety of resolution, like that shown in Figure 1.a, are now available for free or low-cost for much of the globe. TIREM can generate an *RF prediction map* by solving and giving an estimated power value at each pixel in the 2D terrain raster.

For this work, a terrain model is generated by adding building footprints and heights (Figure 1.b) on top of

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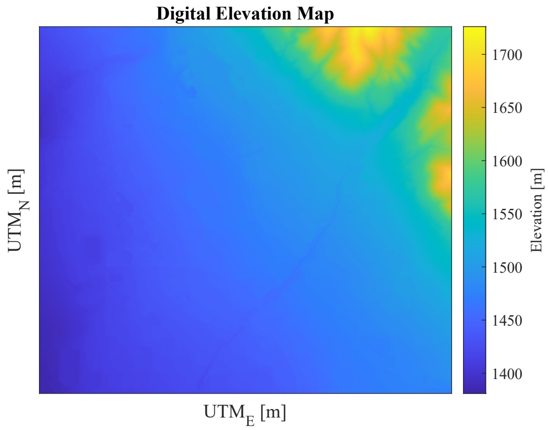
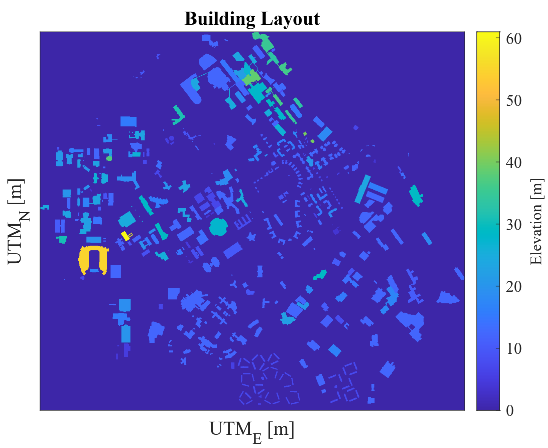


(a) Digital elevation map from the Salt Lake City Valley and Red Butte Canyon mouth.



(b) Georeferenced layout of University of Utah buildings and their heights.

Fig. 1. GIS inputs used to make a hybrid *meta-terrain* model for TIREM.

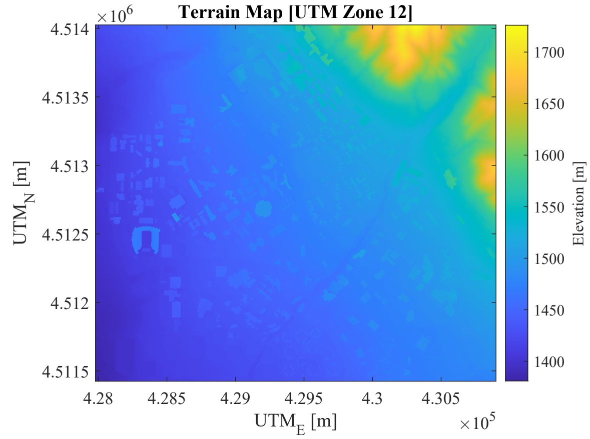


Fig. 2. GIS terrain map of the University of Utah campus. A fusion of terrestrial elevation and building footprint and heights. Map dimensions are roughly 2.5 km by 2.9 km with half meter resolution.

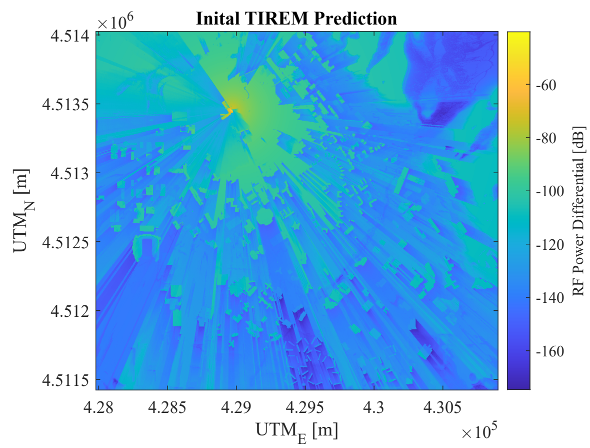


Fig. 3. TIREM generated RF prediction map for the University of Utah. Pixel value represents the losses incurred *only* through the environment.

the digital elevation map (Figure 1.a). In this way, the modified GIS elevation map represents *meta-terrain*, depicted in Figure 2, where buildings and terrain features alike are treated as diffracting obstacles in TIREM's modeling engine. This resulting TIREM model provides the baseline prediction that can be further adjusted with additional correction factors.

The initial, TIREM generated RF prediction map for the University of Utah campus, this work's region of interest, is depicted in Figure 3.

B. Considerations

TIREM is usually employed to generate estimates for long distance and Beyond Line of Sight (BLOS) radio links using a suite of theoretical equations and empirical approximations to perform its calculations [4]. Motivated by a research program that explores next-generation spectrum management in a *radio dynamic zone*, TIREM's prediction abilities are applied to the campus environment at the University of Utah.

Some of the transmit-receive separation distances, however, surpass the minimum threshold recommended for TIREM operation. In these smaller simulation regions, the dominating phenomena considered by TIREM are reduced to free-space propagation, ground reflection, and knife-edge diffraction, further streamlining its calculation process.

However, in a semi-urban or urban environment, TIREM will over-predict path loss due to how it handles obstacles, which it renders as true, infinitely long *knife edges*. This means that approximations for heavily shadowed areas do not consider energy that would wrap around an obstacle or reflect off surfaces that lie near the receiver location, as would occur in an actual scenario [6].

This overly-pessimistic first prediction is still useful, offering a lower bound on expected power received but fails to give a realistic representation of environments dense with buildings. Using measured data from the same environment, correction factors can be easily applied to TIREM's output to further increase prediction accuracy.

III. Measurements

Received Signal Strength Indicator (RSSI) data is collected using the POWDER testbed at the University of Utah [7]. POWDER is a wireless networking platform which allows users to perform wireless device and network experimentation and basic RF research using their entire campus as the testing environment. The network consists of a number of stationary radio nodes and mobile nodes mounted on the buses of the campus transit system. The transmit and receive antenna heights used in this work are 34 and 2 meters, respectively, and feature a 2D-omnidirectional radiation pattern similar to a dipole.

A single stationary node atop a campus building transmits a continuous wave (CW) signal in the Citizens Broadband Radio Service (CBRS) frequency band. The average power received at this frequency is recorded by radios on three different campus buses as they drive through the environment. All data points also record their location via GPS tracking and are thus superimposed on the georeferenced campus building footprint in Figure 4.

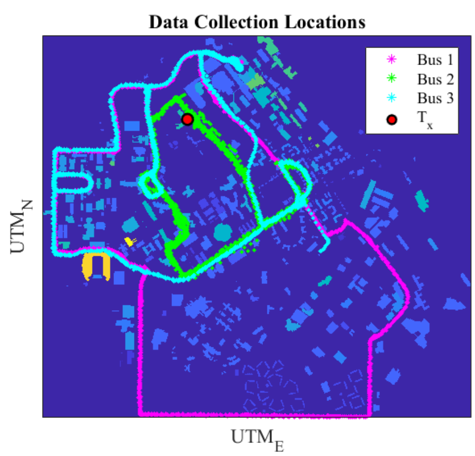


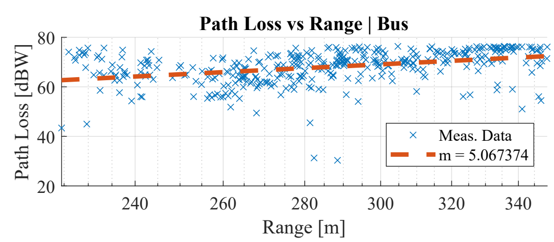
Fig. 4. A georeferenced map of data point locations and transmitter location, superimposed on the layout of campus buildings.

The reported value at each location is the average received power at $f_c = 3550.25$ MHz, the most idle, permissible edge of the CBRS band allotted by the FCC for the POWDER testbed. The downconverted signal is passed through a 20 kHz low pass filter (LPF) to remove neighboring interferers. 2048 measurements are taken and the reported value is the *linear average* of the powers of each sample. On average, a value is recorded every three seconds during a four hour period of bus operation. The data sets collected by each of the three buses are kept separate because the receiver radios, while comprised of identical hardware, are not necessarily calibrated to one another.

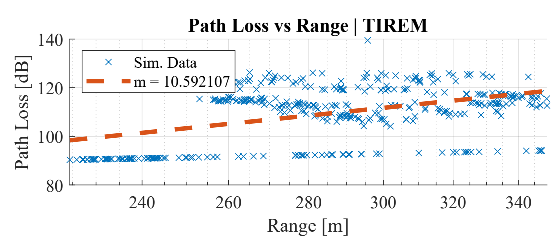
The full list of data entries is further culled upon experiment completion by taking the linear average of all measurements made at the same TIREM pixel location, by removing values beyond the transmitters maximum range, $r_{max} = 350$ meters, and by removing values that are unrealistically far below the noise floor. The relatively tight maximum range is a function of the current Equivalent Isotropic Radiated Power (EIRP) limits placed on POWDER by the FCC. The EIRP of the transmitter was set to around 23 dBm.

The resulting, limited data set now offers a single estimate per location and can be compared directly to the TIREM generated estimate for the corresponding pixel. Using Bus 1 as an example, the measured and predicted values with respect to their range from the transmitter are depicted in Figure 5.a.

The slope of the fit lines in Figure 5 represent the path loss exponent, which for these truncated sets become excessively large. Note, with more data points, its expected that the measured set would converge with a more realistic value which, by TIREM approximation of this set, should be around 3.4. For the culled data sets, it is more important that the 'path loss exponent' approximations of measured and simulated sets are similar.



(a) Measured path loss of Bus 1 data after culling total data set.



(b) TIREM simulation prediction path loss.

Fig. 5. Path loss of measured and simulated data sets w.r.t range between radio locations.

IV. Correction Factor Generation

A. Overview

A favored aspect of TIREM and tools of its type is that its estimates are linearized in log-log analysis. Once running a simulation for a given terrain, it is easy to add or subtract additional power, gain, and loss factors on a per pixel level. It's popular to add losses for particular regions of a TIREM image based on empirical values for appropriate land use classifications (e.g. urban, rural, forested) [8]. This idea is simply stated by Equation (1), where an original TIREM simulation value can be made a more accurate depiction of the real world scenario by adding additional logarithmic correction factors, CF_i.

$$\text{TIREM}' = \text{TIREM} + \sum_i CF_i \tag{1}$$

This idea of applying different losses to varied environments within a TIREM image is still applicable when moving to a microcellular scale, but instead of treating large regions as homogeneous zones incurring equal loss, one can single out certain geometric features in a detailed environment and try to correct TIREM's estimates in other similarly featured locations.

A correction factor (CF) can be generated for any behavior that can be described linearly. Accomplishing this can be done easily using a MMSE method, as stated in Equation (2), where A is a state vector which describes the aspect for which one is trying to compensate for, $\hat{x}$ is the vector of correction factor weights, and b is the error signal between the measured and simulated data. The solution to this equation will always result in the CF weight which will best match, and therefore minimize, the error signal, b.

$$\hat{x} = (A^T A)^{-1} \cdot (A^T b) \tag{2}$$

Once the weights are determined, the correction factor can be calculated via Equation (3) and then readily added to the base TIREM simulation value.

$$CF_i = A_i \hat{x}_i \tag{3}$$

Most importantly, A and b in these equations are vectors of the size of the measured data set. However, if the anticipated A value can be determined for any simulated pixel, even if there is no measurement value to compare it to, the correction factor can still be applied and should ideally make those approximations more accurate. The more data collected and compared, the stronger the reliability of the CF weight becomes.

The immediate state vectors of interest are relatively simple and classify pixels based on whether the channel is Line of Sight (LOS) or a Non-Line of Site (NLOS) scenario.

B. Calibration Offset

It is expected that the most accurate estimates TIREM generates are close range, Line of Sight (LOS) scenarios. In this work, the TIREM simulation is run without any EIRP or gain values and its output purely represents the differential in power between the transmitter and the receive pixel. It is impossible to separate these quantities from the measured values directly, but an meaningful approximation can be gained using this MMSE method.

Using TIREM as a guide, one can determine if any pixel is LOS or NLOS by noting if the maximum height obstacle the in channel path is taller than the LOS path. Once determined, a simple state vector, A, is generated where $A(i) = 1$ if the pixel is LOS and 0 elsewhere.

Solving Equation (2) for this state vector results in a weight which also equals the average calibration value, m_{cal}. An important physical quantity, m_{cal} is the total additional powers, losses, and gains that are added by the transmit and receive systems and *not* the channel.

C. Non-Line of Sight Factors

To then correct TIREM's over prediction of path loss in shaded regions, a similar method to that above is performed. A state vector, A, is generated, where $A(i) = 1$ if the pixel is *NLOS* and 0 elsewhere. Solving this MMSE equation produces a weight, n_{NLOS}, which represents how much more pessimistic TIREM is under these conditions when compared to real world data.

Note, this calculation set is unique because the two state vectors discussed in this section are orthogonal and therefore can be calculated and applied with a single MMSE process where $\hat{x}$ is a two element vector.

D. Results

This process is run on each of the three bus data sets and results in the values and statistics recorded in Table I. The error signal for Bus 1 is graphically depicted in Figure 6 as an example, visualizing how the error is reduced as each correction factor is applied. In Figure 6, *Error* is the original error between measured and TIREM values, *Error'* is the error after the m_{cal} factor is accounted for, and *Error"* is the error after the m_{cal} and n_{NLOS} factors are accounted for.

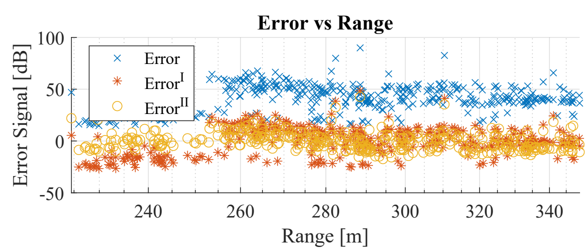


Fig. 6. Error signals between Bus 1 and TIREM data as correction factors are applied.

The standard deviation of the error signal, σ_e, represents how far off, on average, TIREM varies from the actual measured value and serves as a good, single number benchmark for simulation accuracy and reliability.

Without any correction factors, σ_e is undesirably high for all sets and would be difficult for network

Set	σ_e	m_{cal}	n_{NLOS}	σ_e'	$\Delta\sigma_e$
Bus 1	12.85	-24.98	-22.26	8.36	**-4.48**
Bus 2	14.95	-28.67	-25.27	8.05	**-6.9**
Bus 3	10.58	-25.84	-18.38	7.18	**-3.4**

*All values in dB.

TABLE I

MMSE GENERATED WEIGHTS AND ERROR STATISTICS.

designers to trust TIREM outright. However, after these two correction factors are added, a sizable improvement of at least 3.4 dB is seen on all sets, reducing the standard deviation of the error signal to values indicative of a tuned simulation model with good correlation with measurement. With the corrections factors applied, users of TIREM for this environment/scenario can place more confidence in the estimates provided by the simulation tool.

The average *calibration gain*, $|m_{cal}|$, of all sets is around 25 dB. This value represents the culmination of the gains of the transmit power, transmit and receive antenna gains, and other system gains and losses. If the bus data had been taken from a calibrated receiver, this value would represent the actual amount of power leaving the antenna in this direction, an otherwise very difficult value to deduce in real systems.

It is also encouraging that these values are similar for all bus sets, as the receive radio hardware is identical but not calibrated to each other. This value can also be used to normalize future data sets taken from radios which are not operating with similar hardware for comparison or combination purposes.

The NLOS factor suggests that TIREM over predicts path loss in shaded regions by about 20 dB and appears fairly consistent across data sets, resulting in a nice rule-of-thumb correction for TIREM users.

These two examples, though simplistic, provide a great deal of information about how TIREM estimates path loss in this environment. Any conceivable property that can be represented linearly in A can result in further increasing simulation accuracy and deducing important intuitions about a particular microcelluar region.

V. Conclusion and Future Work

This work seeks to best minimize the discrepancies between simulation tools like TIREM and measured data sets taken within the simulated environment. Small-scale TIREM and its unique concerns are discussed and a simple means of increasing simulation accuracy is proposed via minimum mean-squared error (MMSE) methods. This approach extends the utility of TIREM, bringing the technique ever-closer to a true, universal propagation model for all frequencies and environments.

Particular emphasis is placed on TIREM's inherent pessimism when estimating path loss in shadowed regions. A TIREM simulation is run using GIS data to accurately portray the buildings and elevation of a college campus. Channel sounding data is collected using mobile radios as they traverse the environment. The comparison of simulation and measured data sets allows for correction factors that drop the standard deviation of the error signal by as much as 6.9 dB.

The authors intend to perform these calculations with more robust channel sounding methods and attempt to further increase accuracy by finding factors to represent other behaviors (e.g. small-scale fading). More complex methods of regression such as multi-layer perceptrons may illuminate useful features for generating correction factors that would otherwise be difficult to detect outright. Future efforts will be directed towards using deep learning methods to try to automate the detection and classification of certain RF phenomena and their implications on TIREM's RF predictions.

VI. Acknowledgements

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