ECE4370 Class Project: Propagation Modeling in Emerging Shared Radio Spectrum at 3.5 GHz

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1 Introduction

In the United States, government and commercial entities have begun investigating sharing the 3550–3650 MHz military Radar band. However, proposed exclusion zones that limit the interference to and from these S-band radars would severely restrict the usefulness of this band. The key to ensuring successful sharing is robust interference predictions based on accurate and reliable propagation models. This paper presents the results of a comprehensive propagation measurement and modeling campaign for the 3.5 GHz band. Although existing propagation models have demonstrated broad applicability, they each fall short in accurately and reliably describing the measured propagation in this band.

You are a member of a small engineering consulting company that has been contacted by the US government to develop new propagation models for a possible radio frequency allocation at 3.5 GHz. The US has invited your company and a handful of other firms to compete for a lucrative contract that will allow you to build their next-generation propagation modeling software in this band. A trial will be held by studying live measurements from a propagation from a radar tower in central Maryland. After submission, these maps will be compared against real measured data from both indoor and outdoor locations.

The US will provide you with some measurements for a region around an actual 3.5 GHz radar tower so that you can train and test your propagation engine. They will then give you a blank area in the map for your group to predict signal strength. Any extracurricular resource that your company desires to acquire and consult is fair game. This includes satellite photographs, GIS terrain maps, manufacturer's antenna patterns, Tiger data for streets and highways, etc. Be creative.

2 Background and Motivation

The current method of frequency spectrum assignment to specific users leaves much of the spectrum underutilized. Frequency designations within the spectrum remain empty and unused when the primary user is not broadcasting. In 2012, the US President's Council of Advisors on Science and Technology (PCAST) released a report that recommended sharing up to 1.0 GHz of federal government radio spectrum with non-government entities for new Dynamic Spectrum Access (DSA) applications [1]. As a result, the Federal Communications Commission (FCC) in U.S. FCC issued a Notice and Further Notice of Proposed Rule-Making to solicit feedback on the possibility of sharing the 3550—3650 MHz band [2], which had been designated for radars. These notices, however, proposed large exclusion zones to prevent interference from or to the primary user radars. These zones extend inland nearly 200 miles from the U.S. coast, excluding more than 60% of the US population from accessing the band.

One of the key considerations for the successful operation of DSA systems in the ability of DSA secondary user devices to detect the presence of a primary user–even at very low power levels-and either vacate the band or adapt its transmission so as to eliminate interference to the primary user. Numerous researchers have investigated and proposed a variety of spectrum sensing techniques [3], however, typical propagation environments are extremely cluttered and dynamic. Therefore, a vitally important feature for DSA systems is an extremely accurate and reliable propagation model. Such a model would allow DSA devices to precisely predict the effects of: (i) the transmitted signal of either primary or secondary user devices, (ii) the aggregate effects of numerous secondary users on the primary, and (iii) the effects of a high-power primary user on secondary users.

This projoect involves analysis of the results of a comprehensive measurement and modeling campaign for the 3.5 GHz band in Southern Maryland. The measurement campaign objective was to fully characterize the large-scale propagation and determine whether predictive models and measured data would support the reduction in size of the exclusion zones. Over $1,000$ narrowband received signal strength (RSS) measurements were recorded over a 30 km x 30 km area in southern Maryland, characterizing rural, suburban, and over-water scenarios. Measurement results were compared against several standard propagation models, however, these models were unable to fully characterize the entirety of the measured dataset. Although a sophisticated machine-learning or empirical model could be applied, such models would necessarily be site-specific. In an effort to generate a propagation model that was both a better match to the measured data, as well as broadly applicable to a wider range of scenarios, we used a crowd-sourced development approach.

3 Experimental Setup

To characterize 3.5 GHz propagation, a series of Received Signal Strength (RSS) measurements were recorded in and around St. Inigoes, MD. A high-power 3.5 GHz radar located at St. Inigoes was used as the transmitter. The Radar had a rotation time of 4 sec, with a pulse repetition frequency of 1.0 kHz. The radar antenna was horizontally polarized and was installed on a rotating pedestal approximately 7.9 m above ground level. Peak transmitter output power was nominally 90 dBm and the antenna had a cosecant-squared pattern with gain of 32 dBi with 3 dB beamwidth of 3° [4]. To record measurements, a horizontally-polarized dipole receiver antenna was mounted on the roof of a vehicle, approximately 1.8 m above ground level. The antenna had an omnidirectional pattern in the elevation plane, and a 78° 3 dB beamwidth in the azimuth. For approximately 75% of the measurements, the van was moving at speeds ranging from 10–55 miles per hour. The receiver consisted of a bandpass filter, Miteq AFS3 Ultra Low Noise Amplifier, and Tektronix SA2500 Real-Time Spectrum Analyzer with on-board GPS. To record measurements, the spectrum analyzer was operated in time-domain (Amplitude vs. Time) mode, and captured approximately 20 msec of data (approximately 20 radar pulses). the spectrum analyzer was operated in max hode mode, to ensure that the maximum RSS was captured as the radar signal swept over each measurement site. Postprocessing extracted only strongest RSS value from all of the recorded radar pulses from each site. Measurements were recorded at over $1,000$ locations at distances ranging from 70 m to just over 25 km in July and October, 2014.

4 Measurement Analysis

Numerous measurement campaigns have demonstrated the broad applicability of propagation models such as the Log-Distance [5], Irregular Terrain Model (ITM) [6], Extended Hata [7], and Terrain Integrated Rough Earth Model (TIREM) [8]. These models range from the simplicity of a linear regression to measurement dataset (Log-Distance) to the complexity of incorporating terrain, foliage, and atmospherics (ITM and TIREM). These models, however, all make one or more simplifying assumptions, which results in potentially significant errors when they are applied to highly complex propagation environments. Table 1 lists the mean and RMSE error between the Log-Distance, ITM, Extended Hata, and TIREM models when applied to our measurement results. For the log-distance model, a least square fit was applied to the measured data, which resulted in a path loss exponent of $n = 4.2$. For the other models, commercially-available implementations of the algorithms were used, along with commercially-available terrain data for southern Maryland and standard atmospherics.

From Table 1, we observe that the Log-Distance model provides the best overall fit to the measured data, but with significant variability. The ITM and Extended Hata models both produce a relatively small mean error, but have nearly double the variability of the Log-Distance model. The variance is greatest for distances less than 5 km, a region that contained a significant amount of clutter from buildings and foliage. At longer distances, terrain had a much greater influence on the propagation; both the ITM and TIREM models were a much better match to the measurement data.

Table 1: Comparison of 3.5 GHz Propagation Model Accuracy

Error (dB)	Log Dst.	ITM	Ext. Hata	TIREM
Mean	0.1	3.8	5.7	12.8
RMS	11.7	28.4	26.5	20.2
Mean d>5 km	0.3	4.3	7.6	9.0
RMS d>5 km	9.0	15.4	13.1	16.5

5 Data File

There is a project page on the class website that contains this document and a number of supplementary files that will assist you in your design and preparation.

Each structure variable contains a number of fields that specify some useful information about the transmitter. Here is a short summary of the most important fields:

- `ncols` and `nrows`: The number of rows and columns in map `data`.
- `cellsize`: the size of the side of a square cell in meters in `data`.
- `BS_x` and `BS_y`: The column and row coordinates in the raster map corresponding to the transmitter location.
- `data`: A raster map of received powers in dBm, stored in a 2D matrix. Each raster point represents a 20m × 20m area where measured signal strength data has been taken. A value of `NaN` indicates that no received data has been taken at that point.
- `xllcorner` and *yllcorner* and `axis`: marks the extremities of the maps using UTM geodesic northings and eastings
- `TXheight`: height of the transmitter in meters.
- `freq`: frequency of transmission (in MHz)
- `Pt`, `Gp`: transmit power (in dBm) and transmit antenna peak gain (in dBi)
- `TX_Lon` and `TX_Lat`: transmitter longitude and latitude (respectively)
- `uptilt`, `Az_BW`, and `El_BW`: transmit and gain pattern and steering parameters
- `pol`: polarization of transmit antenna

- `RXheight`: height of receiver for all measured locations
- `lats, lons`: latitudes and longitudes of each corresponding pixel on the map
- `dem`: digital elevation map, measured in meters above sea level
- `roads`: digital map denoting road location and vector bearing with respect to north
- `clutter`: clutter classifications for various regions.
  See *http://www.mdp.state.md.us/PDF/OurWork/LandUse/AppendixA_LandUseCategories.pdf* for explanation of the numbers used in this map.

From this data you must construct 2D maps of received signal strength. Here is a useful Matlab command for plotting the existing data map:

```
imagesc(RSSI\_student_map.data);axis equal; axis xy; colorbar;
```

Do not forget to label the axes and add titles for any plots included in your write-up.

Manipulating data in `ReceivedPowerMap` is important for a successful project. Because Matlab uses a (row,column)-format to index 2D matrices, you must always keep in mind that a matrix map must referenced *backwards* with *xy*-coordinates. For example, if the lower-left corner of the map is given the *xy*-coordinate (1,1) and we desire to access the received signal strength at *xy*-coordinate (121,171), we would use the command `RSSI_student_map.data(171,121)`. Since each raster point in the matrix is 20m-by-20m, this point would be 3400 meters north and 2400 meters east of the lower-left corner of `RSSI_student_map.data`.

6 Deliverables

You must prepare a short technical report detailing the results of your study. The report should be in PDF format and prediction maps in Matlab should be submitted electronically to the instructor by the project deadline. The report must include:

- A concise discussion of the problem you are solving and its benefit to society.
- A technical discussion of your propagation model and how you arrived at specific forms and values.
- Documentation of the known received signal strengths and your model's mean/standard deviation errors in dB.
- A short discussion about the practicality and economics of using your model on a nation-wide cellular network.

Be sure to reference any external sources that you consult during the course of this project. This report will be collected on the last Friday before exams (submit electronically).

In addition to the report, you must use your model to construct RF maps for the unknown areas of the map, which will be tested against real measurement data and a mean/standard deviation will be calculated. This submitted data must contain these sites in the format specified in the previous section. Irregularities in the submitted file format will result in *severe* grade reductions.

7 Grading

Each submitted project will be assigned a *Raw Performance Score* based on a formula involving the mean μ and standard-deviation σ errors calculated from measuremed locations on the maps:

$$\text{RPS} = \frac{1}{50}\mu^2 + \sigma$$

With this formula, σ error contributes far more than μ, unless the mean error becomes particularly egregious. All class projects will be ranked in order according to their RPS. Each project is then assigned a ceiling score which is 100 minus a point for each ranked place behind the project with the best RPS. Thus, the project group with the best RPS will have a ceiling score of 100, the project group with the second best RPS will have a ceiling score of 99, the project group with the third best RPS will have a ceiling score of 98, and so on.

Note: Signal strength maps submitted with an incorrect format will instantly be given a bottom-of-class ranking.

Once the ceiling score has been established, your report will be graded on the following criteria:

- Completeness
- **Technical Writing**
- Technical Correctness
- Professional Content
- Research (cite all references)
- Conciseness

Deductions from these categories will be subtracted from the ceiling score. Late projects will not be accepted.

References

[1] Presidents Council of Advisors on Science and Technology, “Report to the president: Realizing the full potential of government-held spectrum to spur economic growth,” Tech. Rep., White House, July 2012.

[2] Federal Communications Commission,, “Amendment of the Commissions Rules with Regard to Commercial Operations in the 3550-3650 MHz Band,” Tech. Rep. FCC 12-148, FCC, December 2012.

[3] D.D. Ariananda, M.K. Lakshmanan, and H. Nikookar, “A survey on spectrum sensing techniques for cognitive radio,” in *IEEE Second International Workshop on Cognitive Radio and Advanced Spectrum Management*, May 2009, pp. 74–79.

[4] Department of Defense, “Military standardization handbook,” Tech. Rep. MIL-HDBK-162B, December 1973.

[5] T. S. Rappaport, *Wireless Communications : Principles and Practice*, New Jersey: Prentice Hall, 2 edition, 2002.

[6] G. Hufford, "The ITS Irregular Terrain Model, version 1.2.2, The Algorithm," Tech. Rep., 1999, Available online at http://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx.

[7] P. McKenna, "A White Paper on Extensions to Hatas Empircal Formulae with Application to a Possible Longley Urban Factor for Aggregate Interference Calculation at 3.5 GHz," Tech. Rep., 2014.

[8] David Eppink and Wolf Kuebler, "TIREM/SEM HANDBOOK," Tech. Rep. ECAC-HDBK-93-076, 1994, Available online at http://handle.dtic.mil/100.2/ADA296913.