

Effects of natural propagation environments on wireless sensor network coverage area

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Abstract— This work presents new near-ground propagation models at 915 MHz based on field measurement data for three naturally occurring environments (open fields, woods and wooded hills). The models are incorporated into a network simulation for randomly distributed transmitting sensors. The effects of the various environments on coverage area are explored for various power transmission levels. This work has implications on quantifying the spatial-temporal resolution of single and multiple hop wireless sensor networks as a function of both transmission power constraints and the environment in which the network is deployed.

I. INTRODUCTION

Wireless sensor networks have been proposed and are being developed for use in industrial, military and environmental monitoring. In these networks, sensors communicate with each other to create ad hoc information collection networks. An ad hoc network is created on the spur of the moment to send information to a base station, or to raise an alarm. These networks are usually short-lived and created in time to respond to a change in stimuli in the area under observation. The majority of work to date on this topic has been for military applications where the sensing devices are very sophisticated and therefore costly. However for industrial and environmental monitoring, cost is of more of a concern. As such, it is very important for these latter applications to know how much of an area is effectively being covered given the number of sensors deployed. For example, heavy signal loss due to harsh environmental conditions or large distance from the receiver will imply unreliable information transmission and/or ineffective spatial-temporal resolution.

In this paper, we explore connectivity issues associated with a low cost environmental sensing network. Specifically, empirical data quantifying the propagation effects for three naturally occurring environments is presented. This empirical data is subsequently incorporated in connectivity models to quantify the sensor network coverage capability as a function of transmission power levels. Factors that affect the propagation loss are the distance from the receiver and obstacles that are strewn on the path of transmission.

Propagation measurements have been performed and models developed for cellular phone frequencies (824-894 MHz) for urban environments [1, 2], however these are not applicable to our sensor scenario for the following two reasons. First, sensors are likely to lie on or near the ground as opposed to a person holding a cell phone (~1.5 m off the ground). Second, the multipath characteristics of an urban environment are significantly different from the three environments considered herein; namely open terrain, woody terrain and woody/hilly terrain. Log-shadow propagation models are developed using linear regression on field measurement data. Using these models, a MATLAB program has been developed utilizing Voronoi diagrams to determine the coverage area of sensor network with and without repeaters.

This paper is organized as follows. Section II details the model used for this study and presents the field data for the three environments. Section III describes the methodology utilized to determine usable area and simulation results. Discussion of the key results of this work is presented in Section IV and Section V concludes with a summary and future work related to this topic.

II. PATH LOSS MODEL AND FIELD MEASUREMENTS

As noted, much work in developing propagation models has been performed for cellular based mobile phone systems. Herein, we present new models specifically for near ground wireless sensor networks operating in the 915 MHz ISM band.

A. The lognormal shadowing model

In this research, the lognormal shadowing model [1] is used to represent the path loss characteristics of natural environments. This model represents the path loss vs. distance relationship through a distance power exponent, n , and random shadowing (or fading) effects through a zero-mean Gaussian function with standard deviation (in dB) of X . Specifically, the path loss in dB, PL, as a function of distance, d , is given by

$$PL(d) \text{ dB} = 10n \log(d/d_0) + X \quad (1)$$

In (1), d_o is the distance associated with a reference measurement. As discussed in the following section, in this work we performed field measurements from which the parameters n and X were obtained for various naturally occurring environments. Once these parameters are quantified, the lognormal shadowing model can subsequently be used to synthesize propagation environments.

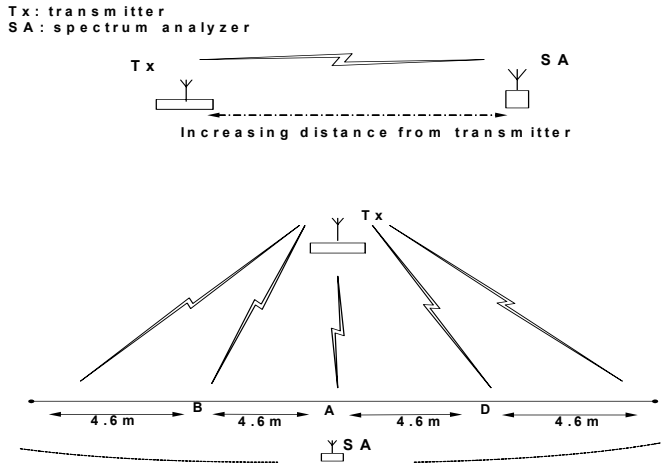
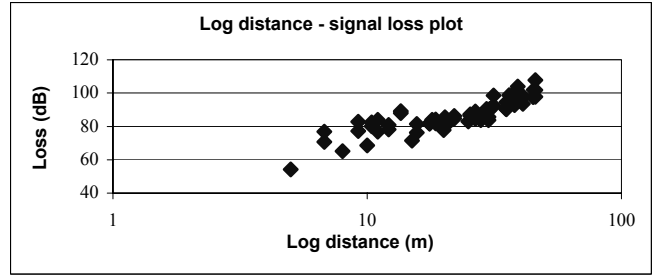


Fig. 1. Schematic diagram of field set-up

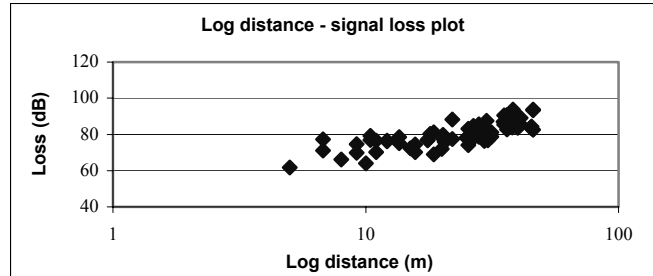
B. Field measurement for loss parameter characterization

The transmitter-receiver setup used to perform field measurements is shown in Fig. 1. A 915 MHz transmitter, having an omni-directional antenna was placed 0.1 m above the lawn. The signal strength at different points was measured using a portable spectrum analyzer (Anritsu MS 2711B) placed on the ground. For three different environments (open field, wooded area and wooded/hilly area), 65 readings were taken throughout an 18.4 m wide and 45 m long grid. Readings were taken first at 5 m directly in front of the transmitter. This position was set to be the reference, d_o . On axes measurements were made at 9 positions from this reference. In addition, off axis measurements were made at ± 4.6 m and ± 9.2 m positions. The measured data is shown in Fig. 2.

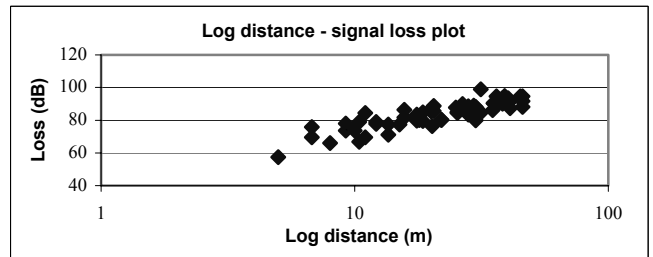
Fig. 2 shows the measured field data for the three environments plotted on a loss (dB) vs. distance (m) semi-log scale (distances range from 5 m to a little over 65 m). From the field data, linear regression was used to determine the loss parameters n and X discussed above. Table I shows the parameters for the three terrains on which measurement were made. Utilizing such empirical data, lognormal shadowing models for each of the three environments can be developed. The advantage of utilizing models is that now simulations can be developed for an arbitrary number of sensors placed in a virtual environment that covers an area of arbitrary size.



(a)



(b)



(c)

Fig. 2. Propagation loss plots from field data: (a) open field, (b) wooded area, and (c) wooded and hilly area

TABLE I
SUMMARY OF FIELD RESULTS

TERRAIN	n (dB)	X (dB)
Open	3.41	4.70
Wooded	2.35	4.37
Wooded and Hilly	2.90	4.17

III. COVERAGE AREA

The scenario investigated herein is that a specified number of sensors are randomly distributed over a specified area. For example, sensors may be deployed via airdrop to measure environmental parameters. The underlying problem is to determine what percentage of the area will be covered by sensors given the propagation characteristics of the environment and the specified maximum link loss between the sensor transmitter and the receiving base station. Under free space environment conditions ($n = 2$, $X = 0$), it would be trivial to determine the maximum distance, d_{max} , a sensor may be from the receiver and the subsequent coverage area will be a circle having radius equal to d_{max} about the receiver. However, for randomly shadowing environments an alternative approach must be taken.

A. Coverage area calculation

Employing the theory of probability, Rappaport [1] showed that the percentage of useful coverage area, $U(\gamma)$, by a base station having a circular radius, R , with an expected received signal threshold, γ , is given by

$$U(\gamma) = \frac{1}{2} - \frac{1}{R^2} \int_0^R r \cdot \text{erf}\left(a + b \ln \frac{r}{R}\right) \cdot dr \quad (2)$$

where

$$a = \frac{1}{\sigma\sqrt{2}} \left[\gamma - P_t + \overline{P_L(d_o)} + 10n \log\left(\frac{R}{d_o}\right) \right] \text{ and } b = \frac{10n \log e}{\sigma\sqrt{2}}.$$

σ is the standard deviation of power loss data in dB (comparable to X in (1)), d_o represents the reference distance from where other measurements are taken, and P_t is the power of the transmitter. Using different n and σ values, expected coverage areas can be found. However, for our simulations, we wish to understand for a specific (but random) distribution of sensors (as shown in Fig. 3a) what the usable area will be. As such, the general number determine in (2) is directly applicable for this particular application.

Herein we employ the use of Voronoi diagrams to calculate the coverage area. The Voronoi diagram is a graph theory tool that divides an area into polygons, each centered on a point as shown in Fig. 3b. Voronoi diagrams have been used to model the ad hoc sensor networks in the terrestrial and marine environments [3, 4, 5]. In addition, the Voronoi diagrams provide a nice aid for visualizing coverage area. Herein, each sensor is assumed to cover the cell as defined by the Voronoi diagram. Note as the distribution of sensors is random, so will be the geometry of the cells associated with the sensors.

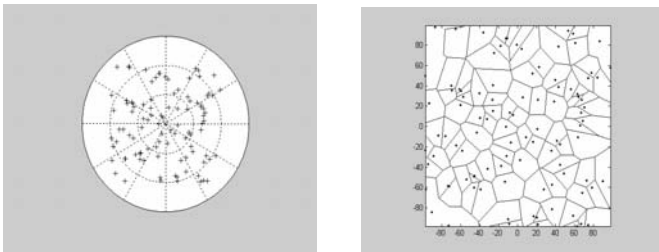


Fig. 3. (a) Random scattering of sensors and (b) resulting Voronoi diagram

B. Coverage area simulation

The simulation consisted of randomly distributing 100 sensors in a specified coverage area (Fig. 3a). Utilizing the empirical data based, log-shadow propagation model, a unique propagation loss was determined for each sensor for each of the three environments (Fig. 4).

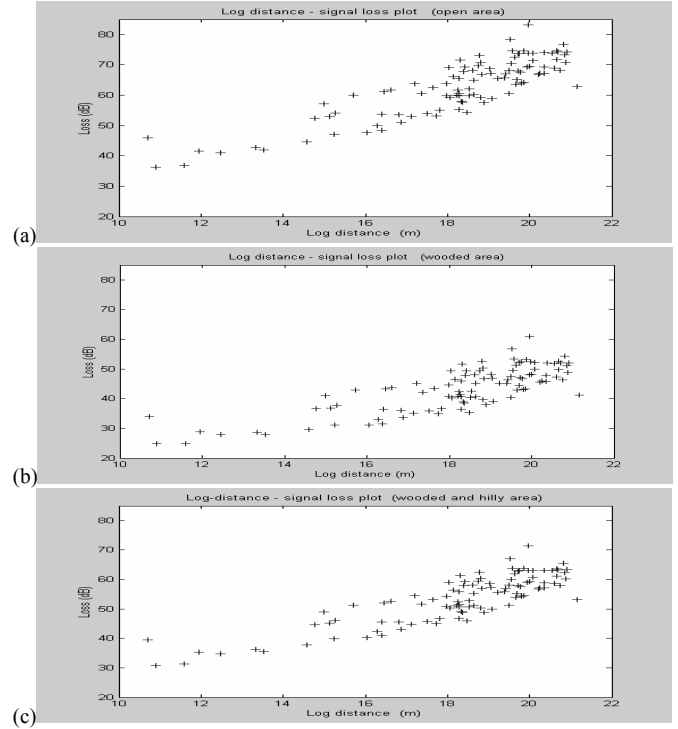


Fig. 4. Modeled loss data for deployed sensors for (a) open field, (b) wooded area, and (c) hilly and wooded area

The coverage area simulation identifies those sensors whose path loss is less than a specified threshold as defining the coverage area. The sum of the areas of the Voronoi cells associated with these sensors divided by the total area give the resulting coverage area ratio. The simulation was run for each of the three modeled environments for four different loss thresholds. Example results are shown in Fig. 5.

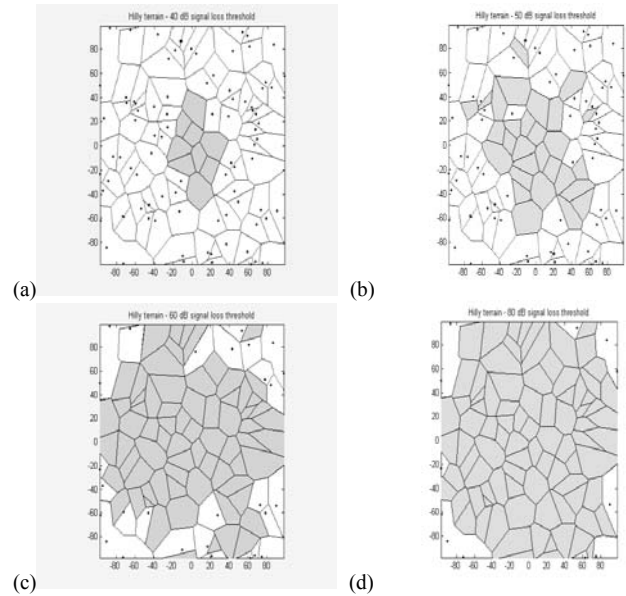


Fig. 5. Coverage area of woody and hilly terrain as a function of threshold: (a) 40 dB, (b) 50 dB, (c) 60 dB, and (d) 80 dB.

The summary of results for all three environments is shown in Table II.

TABLE II
PERCENTAGE COVERAGE AREA WITHOUT REPEATER

THRESHOLD LIMIT (dB)	OPEN	WOODY	WOODY/HILLY
30	0.00	6.27	0.00
40	1.55	27.47	8.47
50	10.77	75.17	26.29
60	31.58	92.61	73.84
80	92.25	92.61	93.22

C. Coverage area improvement with repeaters

For the results presented in Table II a very simplistic single hop network was assumed. The advantage of this type of architecture is that sensors can be of simple transmit only design and the multiple access protocol can be contention based (i.e., pure-ALOHA). However, it is clear that if multiple hops are allowed, each sensor could transmit shorter distances (to a repeater) and thereby at lower signal levels. To illustrate this, a single repeater (at position $x = 36, y = -79$) was added to the environment illustrated in Fig. 5 and simulations repeated. These Voronoi results are shown in Fig. 6. The disadvantage of the multi-hop architecture is that at least some of the sensors (i.e., the repeaters) must have more capabilities than the sensors assumed for the single-hop configuration. For example, the repeaters must obviously have receiver functionality, means of storing data and mean of coordinating data transfer to the base station. That is, although the communication problem has been reduced the computation problem has become more significant.

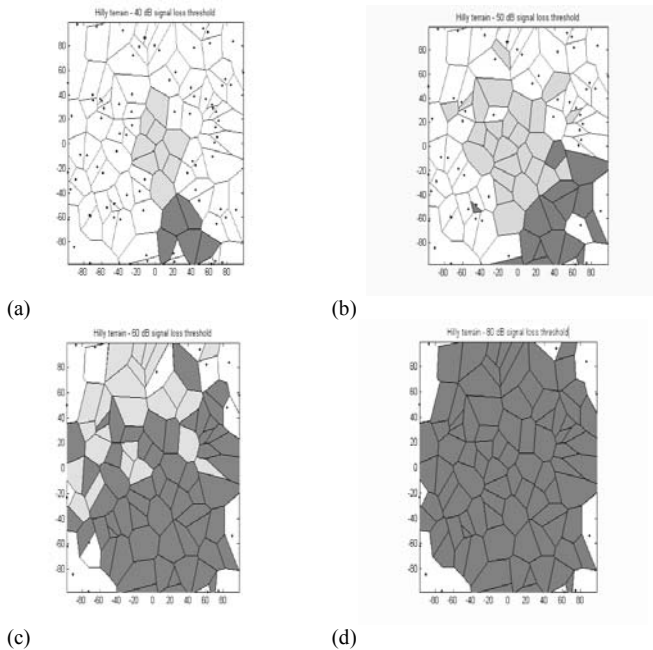


Fig. 6. Coverage area of woody and hilly terrain with an additional repeater as a function of threshold: (a) 40 dB, (b) 50 dB, (c) 60 dB, and (d) 80 dB.

Additional repeaters were placed randomly in the environment (i.e., scattered with the non-repeating sensors) and all three environments were simulated with this hierarchical structure. The aggregate results of multiple simulations are shown in Table III.

TABLE III
COVERAGE AREA (%) OF WOODY/HILLY TERRAIN

THRESHOLD (dB)	NUMBER OF REPEATERS				
	0	1	2	3	4
40.00	7.42	11.97	18.24	22.51	25.42
50.00	32.15	41.46	52.72	61.95	76.88
60.00	87.73	91.30	94.78	97.53	100.00
80.00	100.00	100.00	100.00	100.00	100.00

IV. DISCUSSION

In this section we discuss the significant findings of this work in the order the data has been presented herein.

A. Empirical data results

Table I presents new near ground propagation measurements which indicate that natural environments effect signal propagation differently than might be expected for typical wireless communication systems. Of the three environments, the open field turned out to be the most severely attenuating. This is in stark contrast where open areas for cellular applications exhibit lower path loss and less scattering than wood areas. However, one must keep in mind the application. In cellular systems, the communication link is between the user (~1.5 m off the ground) and a cell tower and thus in a wooded environment the trees would be in the direct path and scatter the energy away from the intended receiver. In our scenario both the transmitter and receiver are below the scattering trees and thus it is hypothesized that the trees in this scenario scatter the energy towards the receiver.

B. Environment simulation

Table IV below compares the propagation parameters for the synthesized environment with those of the measured environment. One will note that for the distribution of 100 sensors the error is small. In short, our simulated environment has propagation characteristics consistent with the actual environment.

TABLE IV
SYNTHESIZED VS. ACTUAL ENVIRONMENT PARAMETERS (dB)

Parameter	n open	X open	n wood	X wood	n hill	X hill
Synthesized	3.69	4.83	2.61	4.50	3.15	4.29
Actual	3.41	4.70	2.35	4.37	2.90	4.17
Error (%)	-7.8	-2.7	-10.0	-2.9	-7.9	-2.8

C. Coverage area simulation results

Table II summarizes coverage area results for the three environments. The table shows coverage area to be the highest in woody environments at all signal thresholds. This is not surprising given that it was the least attenuating of the three environments based on the field measurements. Results also indicate that sensors deployed in an open area would require greater transmission power than if they were deployed in wooded areas in order to achieve the same coverage area. As noted by (2), there are analytical means of determining usable area for cellular wireless systems. Work remains in finding an equivalent expression for the distributed sensor case.

D. Repeater simulation results

From Table III, we see as expected that as the number of repeaters so does the overall coverage area of the system. Also as expected the improvement is most significant when the thresholds are the lowest (i.e., the sensors are transmitting at the lowest power). For example, for a threshold of 40 dB in the woody/hilly environment, the coverage improvement is 61% on average when adding a single repeater and 146% when adding two. We also note that for this threshold and environment that adding more than three repeaters has diminishing benefits. The usefulness of a table such as this is as follows. By performing simulations and creating such tables for a proposed sensor network, one will be able to trade off repeater allocation with sensor transmission power while considering the constraints of the environment in which the network is to be deployed. We contend that this is indeed a valuable tool.

V. FUTURE WORK AND CONCLUSIONS

As noted, the application discussed herein is the cost effective monitoring of environments. To minimize costs, sensors and architectures should be as simple as possible. As such, ongoing work by the authors is to investigate the application of pure-ALOHA to randomly distributed sensor networks. ALOHA is a random access, contention based technique that in our application enables sensors to have simply transmit functionality and as such do not require the expense and power requirements associated with receiver functions (hardware, synchronizations, etc.). Under this scenario, sensors that could be randomly deployed (e.g., through air drop) would transmit sensed information at intervals corresponding to, for example, a randomized transmission interval and/or when the sensed parameter changes. Due to the contention nature of ALOHA it is possible, and even likely, that two sensors will transmit their

data simultaneously resulting in a collision and loss of both pieces of data. The throughput versus load performance of ALOHA is well known for environments where the data is guaranteed to be received as long as there is no collision. However, the environments in which sensors may be randomly deployed in most likely will not have this guarantee. The ongoing work is to quantify these environmental ramifications.

Herein, however, we have presented new results characterizing the propagation environments for near ground deployment of wireless sensor networks. The most significant result is that wooded environments improve the propagation characteristics due to scattering otherwise lost energy towards the intended receiver. This result indicates that systems being deployed in wooded terrain can transmit at lower signal levels than those deployed in open areas and yet achieve the same coverage area. Lower transmission levels enables sensors to last longer in the field and thereby extending the overall life to the deployed network. This work also developed new tools utilizing simulation and Voronoi diagrams to quantify coverage area for sensor networks and thus enabling researchers to predict system performance prior to field deployment.

VI. ACKNOWLEDGMENTS

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