Radio Channel Model of Wireless Sensor Networks Operating in 2.4 GHz ISM Band

JOAO C. GIACOMIN[1], LUIZ H. A. CORREIA[1], TALES HEIMFARTH[1],
GERALDO M. PEREIRA[2], VINICIUS F. SILVA[3], JOAO L. P. DE SANTANA[3]

UFLA - Federal University of Lavras - Brazil
DCC - Department of Computer Science
[1](giacomin,lcorreia,tales)@dcc.ufla.br
[3](viniciusfs,jlucasps)@comp.ufla.br
DEG - Department of Engeneering
[2]geraldop@deg.ufla.br

Abstract. This paper presents a novel signal propagation model of wireless sensor network (WSN) for outdoor open environments. This model can be used in simulators and also in WSN services as localization discovery. The model here proposed produces results with higher accuracy when compared to the models existing in the literature. It is based on the existing double path propagation model (two-ray), but differently from the previous works, it takes into account the directivity of the antennas and the variable reflectivity index of the soil. Experiments confirmed the outstanding results of our propagation model.

Keywords: Wireless Sensor Networks, Wireless Propagation Model.

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1 Introduction

The research effort in the area of Wireless Sensor Networks (WSNs) have been intensified in the past 10 years, specially after industrial standards as IEEE 802.15.4 [7], which is a reference for low-rate wireless personal area networks (LR-WPANs) that use radios in 916 MHz and 2400 MHz unlicensed ISM bands. WSN has specific characteristics and applications that distinguish them form other types of wireless networks. The system is composed of a large number of small autonomous devices, denominated sensor nodes, which use non guided means to communicate to each other forming a network. A Sensor node is equipped with a small processor, a reduced amount of memory and a source of energy as a battery. Therefore, the hardware capabilities and the energy resourse are constrained. The typical radio range of a sensor node is below 100 meters in free space. WSN is a fine grained sensor system that employs a large number of small and cheap sensors which data can be aggregate to give high quality information about the environment.

The energy saving is a primary concern in the development of all communication protocols and programs to control the operation of sensor nodes. A WSN must be able to self-organization, its operation is driven by events and its routing is based on nodes locations. The network is data-centric: users are interested in getting information about environment conditions in specific places, no matter which node is able to send it, in contrast to address-centric networks. Data aggregation depends on a collaborative signal processing involving measurements taken by many sensor nodes located in a given place. Therefore, location information is one of the main service in WSNs. This service may also improve another network functions, such as packet routing.

Location service is the main challenge for wireless sensor networks [9]. The nodes are deployed randomly and each one have to discover its relative position related to the rest of the network in order to establish communication and constitute the network. Rounds of location and routing have to be made periodically because the topology of sensor networks changes frequently, since nodes moves out of their original place or simply die out when energy is depleted.

The development of energy efficient protocols using simulators demands good energy models. Quality of service in data transfer depends on good signal to noise rate (SNR), but transmitting signal with higher power level consumes a larger amount of energy. The question that arises is which are the best transmitter settings in order to achieve good quality of service with minimal energy spending. These settings must be simulated before implemented in real sensor nodes. Since a sensor node uses omnidirectional quarter-wave monopole antenna, there is an attenuation factor of radio signal related to the distance between transmitter and receiver. The signal strength of a radio message decreases as distance increases. Many authors have used propagation models to simulate algorithms of location service, routing, quality of service evaluation and others. The great majority of them are based on Radio Signal Strength Indication (RSSI).

The RSSI is obtained by measuring the signal strength in all realized communications. This information can be converted to a distance estimate if there is mapping from its values to distances [14]. Meguerdichian *et al.* (2001) [9] presented a location algorithm based on multilateration that uses RSSI to estimate distance. The authors demonstrated that accuracies around 5% could be achieved. This algorithm could be largely improved if a better distance estimation would be used.

In this paper we propose a radio wave propagation model for WSN communication signals based on the well known "two-ray" model [10]. The proposed model targets outdoor applications where sensor nodes are placed at a given height above ground and the soil surface is smooth. These conditions are largely encountered in agricultural crop fields, where a WSN is used for monitoring purpose [16].

2 Related Work

The free space propagation model is largely used to simulate wireless communications. The model makes a simple assumption about the attenuation of a propagating signal. In this model, the received signal power (P_R) is an inverse square function of the distance (d) between transmitter (Tx) and receiver (Rx):

$$P_R = \frac{P_0}{d^2} \tag{1}$$

where P_0 is the reference power measured at $1m$ from the sender. The popularity of this model comes from its simplicity [11]. Nonetheless, better models must be used for better accuracy.

Wang *et al.* [15] used the free space model to develop an energy model for simulation of routing protocols focusing in energy efficiency and network lifetime. The model was used to estimate the minimal energy necessary to transmit packets successfully through the network. They used a simple energy model where the radio spent some amount of energy to stay awake and additional energy for the transmission amplifier to achieve an acceptable error rate at the receiver.

Heinzelman *et al.* [6] used a similar model to simulate and compare energy consumption and network lifetime when different clustering protocols were used. For their work, they used a model based on free space propagation model (d^2 power loss) and also multi-path fading (two-ray) model (d^4 power loss). The model was chosen depending on the distance between the transmitter and receiver. The received power derived from this hybrid model was used to adjust the transmission power of the sender. The propagation model was used to derive the energy model (equations 2,3) for simulating network operation. Several routing protocols have their performance appraised using this energy model.

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + lE_{fs}d^2, & d < d_0 \\ lE_{elec} + lE_{mp}d^4, & d \geq d_0 \end{cases} \tag{2}$$

$$E_{Rx}(l) = lE_{elec} \tag{3}$$

where E_{Tx} is the energy spent by the transmitter for sending a message of l-bit length, E_{Rx} is the energy spent by the receiver for the same message. The electronics energy, E_{elec}, depends on factors such as the digital coding, modulation, filtering, and spreading of the signal, whereas the amplifier energy $E_{fs}d^2$ (free space model) or $E_{mp}d^4$ (multi-path model), depends on the distance to the receiver and the acceptable bit-error rate. The authors considered $d_0 = 87m$ as the threshold distance for model changing.

The channel model proposed by Heinzelman *et al.* [6] is based on a simplification of the "two-ray" propagation model as will be demonstrated in this work.

Seidel and Rappaport [12] conducted an experimental research about radio frequency (RF) communication inside buildings and proposed a propagation model denominated shadowing for this scenario. The model is based on the path loss (PL) exponent n indicating rate at which the path loss increases with distance and a zero-mean Gaussian random variable with standard deviation σ, as indicated in equation 4. They used 914 MHz

Building	f (MHz)	n	$\sigma(dB)$
Retail stores	914	2.2	8.7
Grocery store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory Paper/cereals	1300	1.8	6.0

Table 1: The parameters n and σ obtained by Andersen for use in the Seidel's path loss model for different frequency and scenarios [1]

mobile radios with omnidirectional antennas and encountered values for the parameter n ranging from 1.81 to 5.22 and σ (in dB) ranging from 4.3 to 16.3.

$$PL(d) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \quad (4)$$

where $n = 2$ for free space. $PL(d)$ is the path loss with distance d. The parameter n is generally higher for wireless channels. The distance d_0 is a reference distance (1 m) and X_σ is a zero-mean Gaussian random variable with standard deviation σ, both given in dB.

Andersen *et al.* [1] used Seidel's model and conducted experiments in several different frequencies in order to determine the parameters of the model. The objective of the experiments was to determine the parameters for moving stations with different frequencies and environments, at the same floor. Seidel focused in multi-floor measurements. Table 1 presents the results of Andersen's experiments.

In order to use the presented model in WSNs, the parameters must be also estimated for typical sensor network radios. This was done by Giacomin [5] for static nodes. The authors demonstrated that σ in RSSI of radios CC1000 and CC2420 is smaller than 2 dB even when obstacles were in the propagation path. Those radios are present in the widely used Crossbow Mica motes [4].

Slijepcevic *et al.* [13] has used the Seidel's path loss model to conduct a study on location of sensor network nodes employing multilateration and RSSI to estimate distance. The authors consider that a good estimation of distance is the mean value computed on several measurements.

Bahl and Padmanabhan [2] proposed a model to be used in the localization of a mobile sensor node inside a building. Their work is based upon the Seidel's model [12]. They considered the effect of walls positioned in the communication pathways between mobile node and static beacon nodes (equation 5).

WAF is a Wall Attenuation Factor that is determined experimentally; n indicates the rate at which the path loss increases with distance; C is a threshold number of walls and nW is the number of walls between transmitter and receiver. The authors come out with values of n ranging from 1.45 to 1.76. A good accuracy on user location estimation was achieved. The resolution of the system was from 2 to 3 meters.

$$P(d)[dBm] = P(d_0)[dBm] - 10nlog\left(\frac{d}{d_0}\right) - \begin{cases} nW * WAF, & nW < C \\ C * WAF, & nW \geq C \end{cases} \quad (5)$$

The two-raw ground reflection model [10] assume that the electromagnetic waves achieve the receiver antenna through two different paths. The first path, called line of sight (LOS), represents the portion of the electromagnetic energy conveyed directed from transmitter to receiver. The second one is the portion of the energy reflected on the soil surface before achieving the receiver.

The waves reflected in the ground suffer attenuation and phase displacement due to the ground characteristics. This is expressed by a multiplicative factor ($\mathbf{R}$) which is a complex value. In most of works, authors just consider inversion in phase and a constant attenuation given a real value to $\mathbf{R}$. When the attenuation is not considered, $\mathbf{R} = -1$.

In our work, we proposed improvements over the existing propagation models resulting in higher accuracy. Previous methods neglected the variable reflective index of the soil and the directivity of the radio antennas, considered in our model.

3 VSR Propagation model

In this section, we introduce our VSR (Variable Soil Reflectivity) model. It is an improvement of the multipath propagation model (two-ray) [10] in order to increase its accuracy. Our model considers the distance of antennas from the soil surface, their directivity and the soil reflection properties (variable reflectivity). The proposed model is applicable in outdoor open scenarios, as agricultural fields and parking areas.

In an non-directional transmission from an isotropic source, the distance between the transmitter (Tx) and receiver (Rx) plays an important role when determining the power loss suffered by the traveling wave as stated by Friis transmission formula [10]. If Tx and Rx are close to soil surface, we can achieve a more accurate model when considering the portion of the radiated signal that is reflected by the ground back to the receiver antenna. This is outlined in Figure 1.

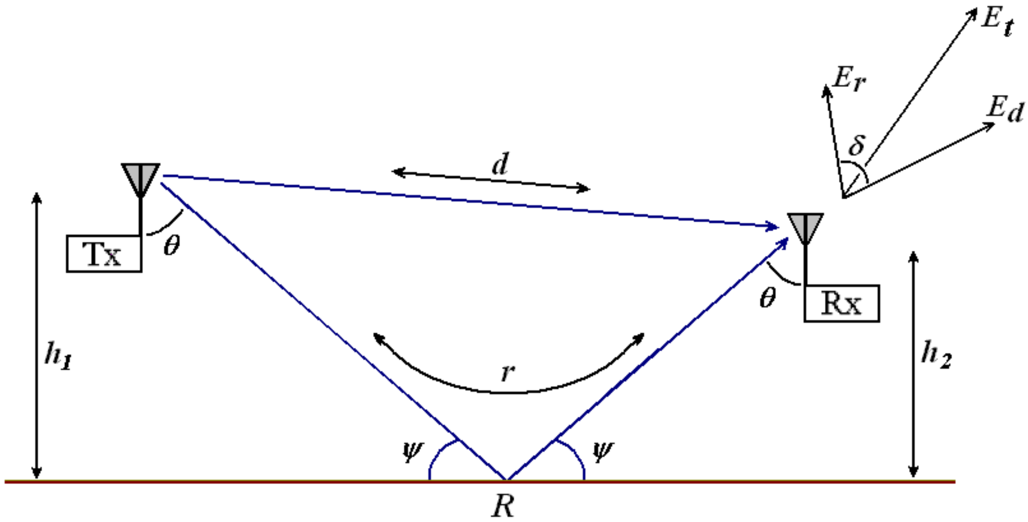

Figure 1: Two-ray propagation schematic - the first ray (distance d) is LOS and the second (distance r) is reflected on ground. Electric fields E_d, E_r and E_t are represented in fasor form.

This model considers the interaction between the two electric fields that reach the receiver antenna. The first one (E_d - electric field direct) is related to the direct propagation (line of sight) signal, and the second one (E_r - electric field reflected) is related to the signal reflected in soil surface. The height of the transmitter antenna is denoted by h_1 and from the receiver antenna is denoted by h_2. R is the ground reflection index and is expressed by a complex value, $|\mathbf{R}| \in]0, 1[$. The total electric field (E_t) results from E_d and E_r interaction. The equation 6 presents how its intensity can be computed.

$$E_t = \sqrt{E_d^2 + E_r^2 + 2 \cdot E_d \cdot E_r \cdot \cos(\delta)} \qquad (6)$$

Here, δ is the phase difference between E_r and E_d . In this case δ can be given by:

$$\delta = \frac{2 \cdot \pi}{\lambda} \cdot (r - d) \qquad (7)$$

for wave length λ, path length r of the reflected signal and d as the path length of direct signal.

The radio waves emitted by omnidirectional antenna used in sensor nodes propagates in all directions resulting in a reduction in the electric fields intensity as a function of distance. The intensity of electrical field of the direct path (E_d) can be expressed as:

$$E_d = E_0 \cdot \frac{1}{d} \qquad (8)$$

and the intensity of electrical field of reflected path (E_r) as:

$$E_r = E_0 \cdot \frac{1}{r} \cdot R \cdot D \qquad (9)$$

where E_0 is the reference value for the electrical field intensity, measured 1 meter from the source (free space condition). R is the modulus of ground reflection index and D is antenna directivity.

We can compute the distance r propagated by the reflected signal (see Figure 1) as function of d, h_1, h_2, using:

$$r = \sqrt{d^2 + 4 \cdot h_1 \cdot h_2} \qquad (10)$$

When the distances r and d are large compared to the antennas heights h_1 and h_2, the difference between r and d in 10 can be approximate to:

$$r - d = \frac{4 \cdot h_1 \cdot h_2}{r + d} \cong \frac{2 \cdot h_1 \cdot h_2}{d} \qquad (11)$$

With a very large d, the reflectivity is close to -1 ($R \cong -1$) [10]. The total electric field E_t on the receiver antenna will decay as a inverse function of the square of d:

$$E_t = \frac{4\pi \cdot E_0 \cdot d_0 \cdot h_1 \cdot h_2}{\lambda \cdot d^2}; \quad d > \frac{20 \cdot h_1 \cdot h_2}{\lambda} \qquad (12)$$

The received signal strength (electromagnetic power received in Rx), is a square function of total electric field. It can be normalized to a reference power value

(P_0), measured at 1 meter from the source in free space. In this case, P_t is given by:

$$\frac{P_t}{P_0} = \frac{1}{d^4} \tag{13}$$

or expressed in decibels related to 1 mW:

$$P_t[dBm] = P_0[dBm] - 10 \cdot 4 \cdot \log(d) \tag{14}$$

Since the radio range in the majority of wireless sensor networks is less than 100 meters, the antennas height (h_1 and h_2) would be in the same order of the wave length(λ) in order to satisfy the condition stated in equation 12. This means that the approximation $n = 4$ used by Heinzelman [6] is not a good choice for wireless sensor networks simulations.

Another weakness of the presented methods lays on the considered reflectivity of the ground: values different from $\mathbf{R} = -1$ should be used in the computation of electric field and received power. Moreover, directivity of antennas different from the unit ($D < 1$) should be also taken into account. The value of $\mathbf{R}$ depends on antennas polarization, dielectric constant of soil and the incidence angle of the waves on the ground. Figure 2 presents the real and imaginary parts of $\mathbf{R}$ ($\mathbf{R} = R + j.S$) for angles ranging from 0.1^o to 90^o considering vertical polarization and dielectric constant $\mathbf{DC} = 16.1 + j3.4$ [3].

When the rate between transmission distance and antennas height become large, the soil reflectivity approximates $\mathbf{R} = -1$. In addition, the imaginary part of $\mathbf{R}$ is negligible when compared to its real part in almost all angles in the range of Figure 2. Then we can roughly model the soil reflectivity presented there as a real value:

$$R = \begin{cases} 0.5, & \Psi \geq \pi/4 \\ 6\frac{\Psi}{\pi} - 1, & \Psi < \pi/4 \end{cases} \tag{15}$$

A more accurate computation of total electric field is:

$$E_t = E_0 \left(\frac{1}{d^2} + \frac{R^2 \cdot D^2}{r^2} + 2\frac{R \cdot D}{d \cdot r} \cos(\delta) \right)^{\frac{1}{2}} \tag{16}$$

The total received power (P_t) is proportional to the square of the eletrical field:

$$P_t = P_0 \left(\frac{1}{d^2} + \frac{R^2 \cdot D^2}{r^2} + 2\frac{R \cdot D}{d \cdot r} \cos(\delta) \right) \tag{17}$$

leaving to:

$$P_t = \frac{P_0}{d^2} \left(1 + \frac{R^2 \cdot D^2}{(r/d)^2} + 2\frac{R \cdot D}{r/d} \cos(\delta) \right) = \frac{P_0}{d^2} T \tag{18}$$

Directivity D can be approximated as a square function of $sin(\theta)$, as expressed in equation 19, where θ is the angle of propagation relative to the direction of the antenna. In Figure 1 the angle θ is the same for Tx and Rx due to symmetry.

$$D = \sin^2(\theta) \tag{19}$$

Considering $d_0 = 1\ m$ as the reference distance, received power (P_t) can be expressed in decibels relative to 1 mW:

$$P_t[dBm] = P_0[dBm] - 20 \cdot \log(d) + 10 \log(T) \tag{20}$$

A common environmental application uses sensor nodes positioned at the same height ($h_1 = h_2 = h$) above a flat soil surface. This is the reality in WSN, since there is no differentiation in the sensor nodes. Figure 3 presents the graphs of tree propagation models, free-space (LOS), two-ray and VSR, proposed here. The graphs were plotted considering $P_0 = -55\ dBm$ and $h = 1.4\ m$. For two-ray model, it was considered soil reflectivity as a constant $R = -0.7$ and isotropic antennas ($D = 1$). For VSR model the soil reflectivity presented in Figure 2 was considered. It is important to observe that in very short distances ($d < h$), the VSR graph is close to the free-space, caused by low antenna directivity. In medium distances ($h < d < 10h$) VSR values oscillates around free-space, but with less intensity than the values obtained with the two-ray model. In long distances ($d > 10h$) VSR approximates the two-ray model. We want to highlight that the attenuation in distances larger than 200 meters is 40 dB per decade ($n = 4$) for the VSR and two-ray models and just 20 dB per decade ($n = 2$) for free-space.

4 Experimental results

In order to validate the presented model, we conducted an experiment in an open outdoor area. We assured the absence of any obstacle (pavement, plants, etc) for the experiment. Our wireless sensor network was composed by MicaZ motes [4] transmitting with 0 dBm. The nodes were positioned in two points as depicted in Figure 1. Two nodes (N_1 and N_2) were placed in Rx position and other two (N_3 and N_4) in Tx position. The nodes were mounted 1.3 meters from the ground.

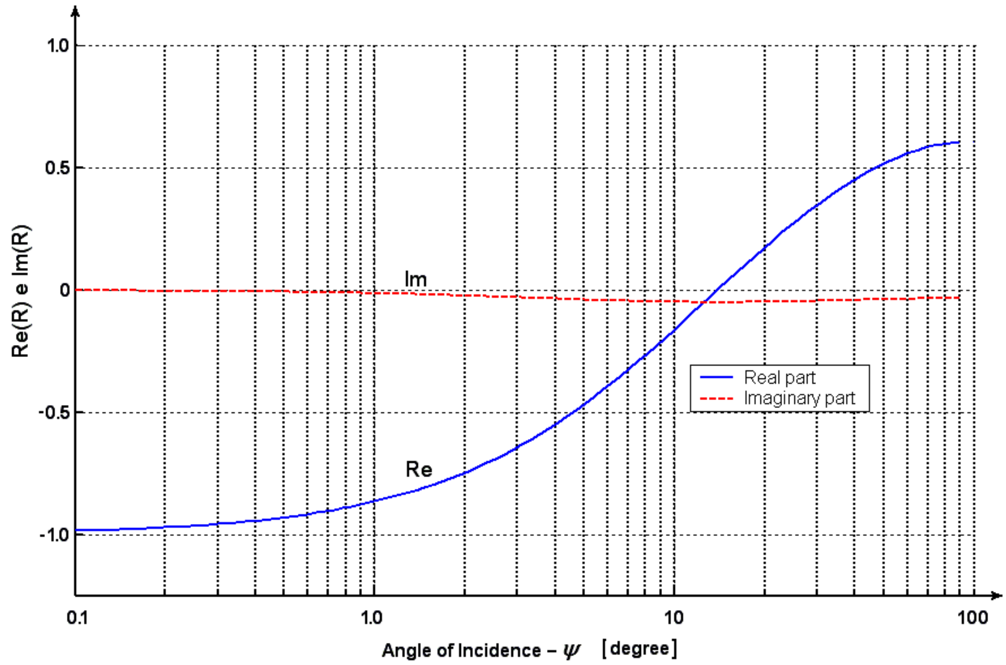

Figure 2: Real and Imaginary parts of soil reflectivity index ($\mathbf{R}$) for a moisten soil (22%) and $1.25\ GHz$.

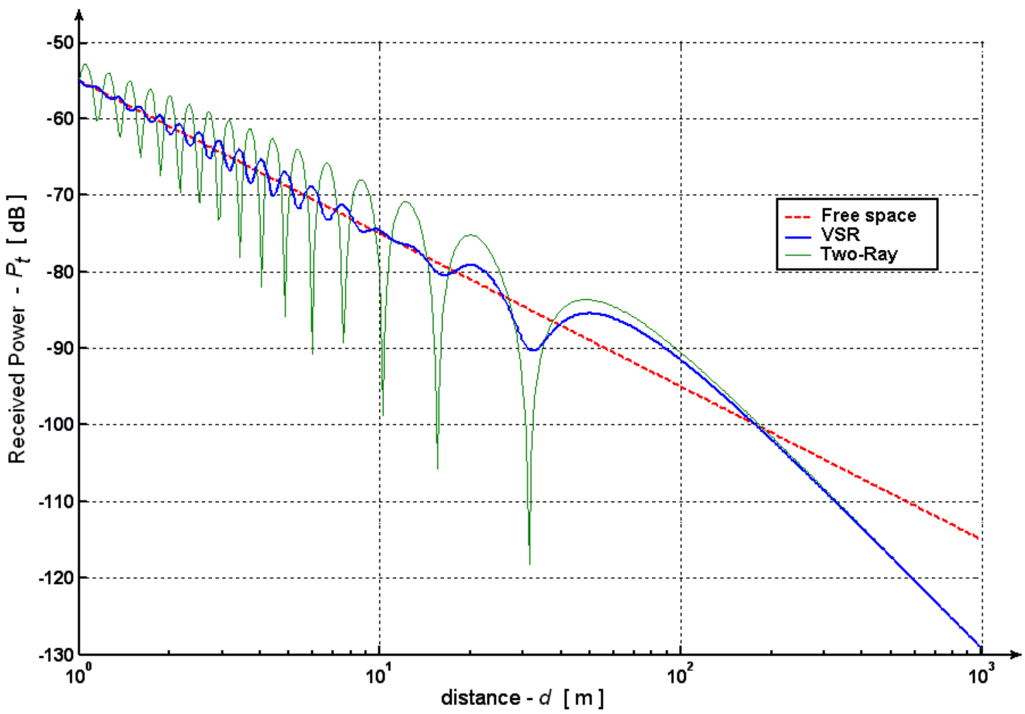

Figure 3: Received power (P_t) as a function of distance (d) considering free-space, two-ray and VSR models. $P_0 = -55\ dBm$, $h = 1.4\ m$.

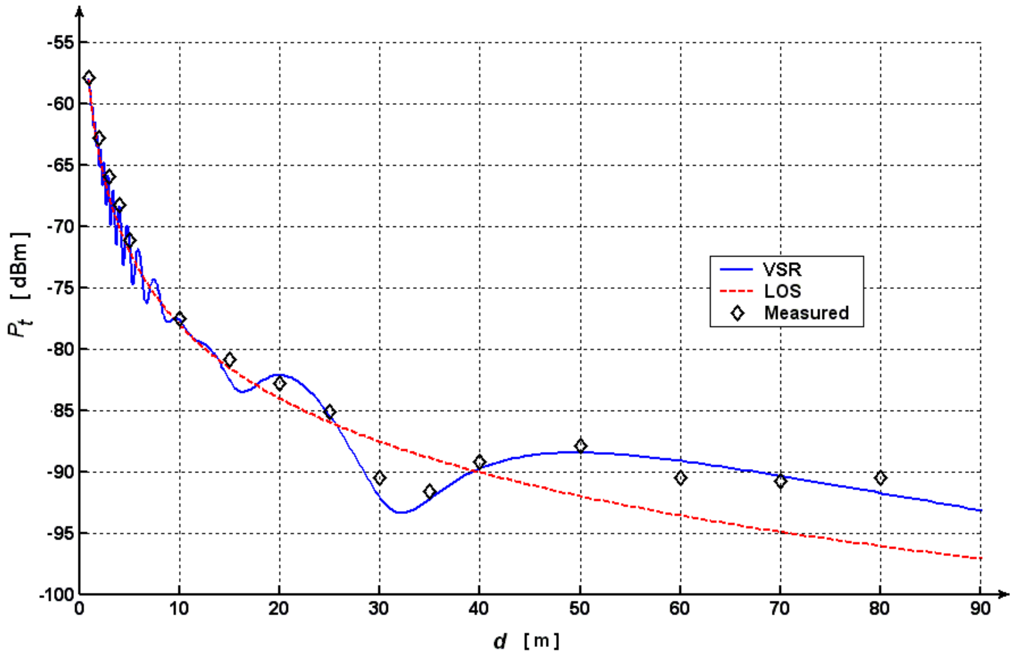

Figure 4: Measured received power with a MicaZ wireless network in outdoor unobstructed area. Models of free-space (dashed line) and VSR (solid line) for sensor nodes at 1.4 m high and frequency 2400 MHz.

N_1 and N_2 transmitted short packets to N_3 and N_4. The last two also transmitted short packets to N_1 and N_2. All nodes measured received signal strength for every received packet. Every four measurements were send to a base station (N_0) connected to a computer where data was collected. Measurements were made for 16 different distances, d = {1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80} m. The measurement set was repeated fifty times for each distance. We computed the mean values and standard deviations. Mean values stayed in the range $-91 < P_t < -57$ dBm and standard deviations were less than 2 dB.

The Figure 4 presents the values obtained in our experiment. The values are the average of all measurements made by four nodes in each distance. In the same figure, we presents the resulting received power obtained by the two-ray model considering $h = 1.4$ m and soil reflectivity as presented in Figure 2. It is important to state that electromagnetic waves penetrate about a wave length the ground before reflecting back to the receiver antenna [8]. In the same figure, we also presented the received power considering only the line of sight (LOS) communication.

In order to evaluate and compare the models described here, the coefficient of determination (R^2) was used. Table 2 presents R^2 values calculated for several models: free-space ($n = 2$), two-ray (with $R = -1$), two-ray (with $R = -0.5$) and VSR. The Seidel's model was used to estimate P_0 and n that best fit to measured values, resulting in $P_0 = -57.9$ dBm and $n = 1.894$.

Model	R^2
Free-space ($n = 2$)	0.9487
Seidel's model ($n = 1.894$)	0.9645
Two-ray ($R = -1$)	0.8275
Two-ray ($R = -0.5$)	0.9426
VSR	0.9923

Table 2: Coeficient of determination (R^2) of several models adjusted to measured values of received power as a function of distance

5 Conclusions

In this work, we presented VSR, an improvement in two-ray propagation model. The proposed model is more accurate than existing ones [6, 11]. Wireless sensor network simulators may use the proposed model to get more realistic results. In addition, location service algorithms also profit from the presented model.

Using our model, it is possible to simulate real world effects on node reception that are not embraced by the existing models. For example, in some scenarios a given node can communicate to a distant neighbor but not to a closer one. In Figure 4, this effect can be seen if we consider the threshold for a successful reception of $-90\ dBm$. In this case, the node will be able to communicate to those located 40 or 50 meters away but not to nodes located 30 or 35 meters from the sender.

As future work, we want to investigate other factors that affect the strength of the received signal. For example, environmental temperature must be investigate and modeled for the small radios used in Mica Motes. For location purposes this will not bring any improvement since the influence of temperature affect equality all the radios in the network.

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