An Accurate Radio Channel Model for Wireless Sensor Networks Simulation

Alejandro Martínez-Sala, Jose-María Molina-Garcia-Pardo, Esteban Egea-López, Javier Vales-Alonso, Leandro Juan-Llacer, and Joan García-Haro

Abstract: **Simulations are currently an essential tool to develop and test wireless sensor networks (WSNs) protocols and to analyze future WSNs applications performance. Researchers often simulate their proposals rather than deploying high-cost test-beds or develop complex mathematical analysis. However, simulation results rely on physical layer assumptions, which are not usually accurate enough to capture the real behavior of a WSN. Such an issue can lead to mistaken or questionable results. Besides, most of the envisioned applications for WSNs consider the nodes to be at the ground level. However, there is a lack of radio propagation characterization and validation by measurements with nodes at ground level for actual sensor hardware. In this paper, we propose to use a low-computational cost, two slope, log-normal path-loss near ground outdoor channel model at 868 MHz in WSN simulations. The model is validated by extensive real hardware measurements obtained in different scenarios. In addition, accurate model parameters are provided. This model is compared with the well-known one slope path-loss model. We demonstrate that the two slope log-normal model provides more accurate WSN simulations at almost the same computational cost as the single slope one. It is also shown that the radio propagation characterization heavily depends on the adjusted model parameters for a target deployment scenario: The model parameters have a considerable impact on the average number of neighbors and on the network connectivity.**

Index Terms: **Channel modeling, near ground propagation, simulation.**

I. INTRODUCTION

Wireless sensor networks (WSNs) have to address technical challenges similar to those of mobile ad-hoc networks (MANETs): Decentralized multi-hop networks that employ a common transmission channel. But WSNs goals are quite different from those of MANETs due to the fact that the nodes have to collaborate in a distributed manner to set-up and manage the network and to monitor physical parameters from the deployment scenario [1]. Consequently, challenging issues arise.

- There will be specific traffic patterns driven by sensor measurements. These measurements will depend on the dynamics of the physical parameters related to the environment. Intuitively, there is a complex relationship among the behavior of the physical magnitude to be measured, the sensor placement, and the network connectivity.
- The energy is the most important issue. If a node runs out of energy, it leaves the network and degrades its operation and its expected lifetime. Therefore, related to node energy consumption, network lifetime is a fundamental metric. Since all the nodes collaborate for the same goal, there is a dependency between the network performance and the network lifetime with the actual number of neighbors of a node (connectivity).

As we shall see in Section V, network connectivity (Fig. 4) and the number of neighbors per node (Table 2) are related to the radio propagation characteristics of the target scenario.

In this paper, we focus on two problems related to study of WSNs.

1. Analytical studies of WSNs are complex, even unfeasible in many cases. Besides, deploying field test-beds to study the actual behavior of protocols implies a great effort [1], [2]. Consequently, WSNs are commonly studied through simulators. These tools allow a fast way to test new applications and protocols in the field. Indeed, there has been a recent *boom* of specific simulation tools [3]. However, it has been shown that wireless simulation results are heavily influenced by the selected radio channel model and its parameters [4]. The problem is twofold. On one hand, protocol behavior and performance (specially for routing protocols) rely on the links a node can establish. That is, the number of reachable neighbors of a node, which depends on the accuracy of the radio model. On the other hand, including accurate models (e.g., a model based on actual measurements) constraints the simulation scalability [5]. For example, [6] shows scalability problems of the popular ns-2 simulator [7] working just with 100 nodes. As an aside problem, simple models may be suitable in some cases and perform well enough, but still they could be inaccurate due to a poor, unrealistic configuration of model parameters [8]. Therefore, there is a need for accurate enough and computationally efficient radio channel models for WSN, which must be configured with scope-matched parameters.
2. In the literature, almost all studies of radio propagation assume that the devices (the antennas) are placed one meter or more above the ground. However, this is not the expected case for WSNs. In fact, most envisioned applications place the sensors just over the ground. But there is a lack of radio models for this situation [9].

This paper proposes the use of a two slope path loss model as an accurate but still computational-feasible near ground radio channel model to feed more realistic WSNs simulations. Moreover, the two slope path loss model has been validated by real measurements. Finally, parameters for this model in three common scenarios are provided. The outdoor scenarios selected

Manuscript received July 31, 2005; approved for publication by Kung Yao, Guest Editor, November 29, 2005.

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have been a ground plane, a university yard, and a grass park. The methodology used has been as follows: At each scenario, the propagation losses have been measured. Then, the parameters of two synthesized radio channels, which fit our measurements, have been computed: Firstly, a one slope log-distance path loss model, which is commonly employed in current simulation frameworks (e.g., ns-2), and secondly, a two slope log-distance path loss model that provides a better accuracy with a similar computational cost.

The rest of the paper is organized as follows. Section II contains the related work. In Section III, the measurements are presented for the three selected scenarios. Section IV describes the parametric adjustment for the models proposed. Next, Section V discusses the impact of the selected radio models and parameters on simulation results. Finally, Section VI presents the main conclusions of this work.

II. RELATED WORK

As stated above, in most WSN, the nodes are over the ground and their antennas are a few centimeters over the ground. As far as we know, there is a lack of measurements for this situation, that is, near ground measurements [9] in scientific literature. The vast majority of the studies place antennas at a height greater than one meter [10]. In addition, there is an increasing interest in evaluating and measuring the actual link behavior and its effect and influence on WSNs. In [11], Zhao and Govindan provide one of the first works with experimental measurements. They show that there exist some areas within the communication range where reception over time is highly variable and unreliable, but they do not give any explanation of their findings. Empirical measurements of link quality shown in [12] reflect the impact on routing protocols and the need for the implementation of a link quality estimator in nodes. Recently, Reijers *et al.* [13] show more empirical results of extensive link layer measurements with the eyes nodes but they do not provide any channel model. In [14], it is reported that radio irregularity due to the non-isotropic properties of antenna directivity and to the heterogeneous properties of node hardware have a remarkable influence on the routing protocols. They propose the radio irregularity model (RIM) that takes into account these effects.

Regarding simulations, three related problems should be considered.

1. Protocol performance for wireless links depends on the used radio model. Kotz and Newport [4] show the differences in ad-hoc routing protocol performance results when using simple and more complex radio models.
2. Computation of radio propagation degrades performance and scalability of wireless simulators. Takai [5] also describes the effects of different radio models on protocol evaluation but including their impact on execution time. Three models are evaluated: Free-space, Rayleigh, and a detailed statistical impulse response model. It is concluded that the detailed statistical model dramatically increases computational cost for the simulation. Naoumov [6] reports scalability difficulties of ns-2 due to unnecessary computation of propagation losses. Algorithmic optimizations are provided to alleviate the problem.
3. An inappropriate configuration of model parameters may cause misleading results. Perrone [8] warns about the fact that model parameters are too often chosen without a clear reason. In this sense, one of the Newport suggestions [4] is that the simulation model should match the expected environment. Another recommendation is to use real data when available to feed simulations.

As it can be seen, some tradeoff among accuracy, performance, and scalability is needed. Implementation optimizations help to balance the tradeoff. ns-2 is a very popular simulator that provides a good example of this combination of techniques. It uses the "limited interference" assumption. Interferences are only considered if nodes are within a certain range (carrier sense threshold). There is an underestimation of the noise level beyond range. This is the most used assumption in simulators, because it may significantly reduce the set of nodes to compute propagation for a given transmission. The algorithms of Naoumov [6] are optimizations to compute this set of nodes in range per transmission.

ns-2 supports, among others, a log-normal channel model, which is considered a reasonably accurate model [4]. But the question of how to choose the model parameters still remains. ns-2 only provides common ranges for the parameters of this model, and it is the researcher who must select the most appropriate. ns-2 also includes the two-ray ground reflection model, which uses two exponents 2.0 for near field, and 4.0 for far field. However, these values are usually different and environment dependent, as it will be later shown in our results.

In this paper, we address all these issues, validating models that accurately describe propagation in WSNs, with moderately low computational cost, and providing values for their parameters in common scenarios.

III. MEASUREMENTS

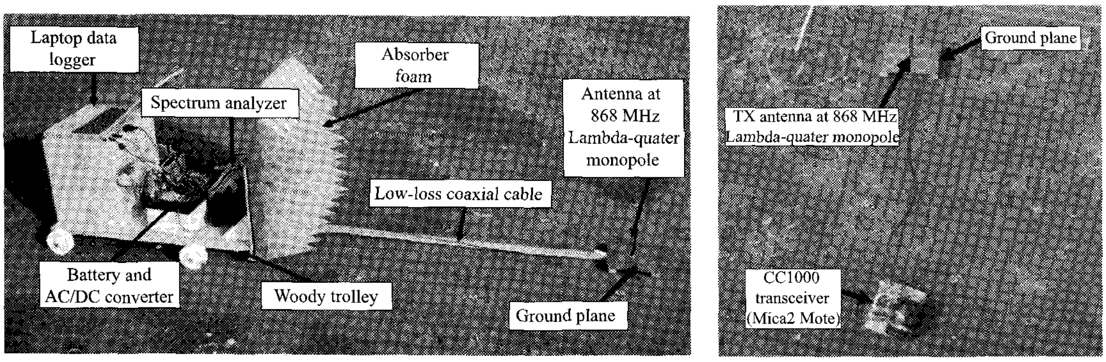
This section explains our measurements. Firstly, a description of the sensor hardware and of the measurement equipment employed is provided. Then, a discussion on the methodology follows.

A. Sensor Devices

The nodes used have a low power narrow-band RF transceiver [15] (as the widely used Mica2 Motes [16] working at 868 MHz (Europe) or 915 MHz (USA) in the free industrial, scientific and medical (ISM) frequency bands with a maximum radiated power of 5 dBm. Our research has been conducted at 868 MHz; however, the propagation characteristics and conclusions can also be extended to 915 MHz (frequency variation is very low, around 5%). The transmission rate for these systems is very low (a few dozens of kbps) and the symbol period much higher than the RMS delay spread, therefore a flat slow fading channel can be assumed [10].

B. Measurement Equipment

The channel sounder set-up is presented in Fig. 1. A Mica2 Motes [16] transceiver is used as transmitter and a spectrum analyzer (ROHDE and SCHWARZ FSH-3) is used as receiver,



(a) (b)

Fig. 1. Picture of the channel sounder set-up in the ground plain scenario: (a) Receiver, (b) transmitter.

and both of them are placed just over the ground. Taking into account that the goal of this work is to characterize the near ground wireless channel, but not the effects of the antennas, two $\lambda/4$ monopoles placed over two $\lambda/4 \times \lambda/4$ ground planes are employed (at 868 MHz, the wavelength λ is 0.33 m). Both antennas are connected to the transmitter and to the receiver by a low-losses coaxial cable, and they are located far from the hardware to minimize its influence (Fig. 1). The receiver consists of a laptop, a spectrum analyzer and batteries mounted in a woody trolley with absorber foam to reduce near scatter (Fig. 1). The receiving antenna is placed at one and a half meter away from the trolley, whereas the transmitting antenna is one meter away from the Mica2 transceiver. The transmitter sends a constant carrier of 5 dBm (maximum radiated power) at 868 MHz and the spectrum analyzer is set to this central frequency.

C. Scenarios and Measurement Methodology

A typical wireless sensor network application running in an outdoor scenario has been considered for this work. Examples of these applications are habitat monitoring, disaster relief, or a location and navigation system for explorer robots in Mars, etc. These applications have in common that Motes/nodes are deployed randomly throughout the area. We also assume that in these networks the nodes are static and channel variations are due to the environment, which can be considered quasi-static (slow changing assumption).

Three different scenarios/environments have been selected: A huge ground plain (quasi ideal flat ground), a university yard surrounded by four-story buildings, and a grass park slightly curved. For all scenarios, the same measurement procedure has been applied: The transmitter was fixed in several random positions, and for each position, the receiver has been separated from the transmitter following a straight line up to signal to noise rate (SNR) was 10 dB. For our spectrum analyzer, the measured noise was −95 dBm for a 10 kHz intermediate frequency bandwidth. Along the straight line followed by the receiver, the samples were taken every 0.5 meters up to a distance of 3 meters from the transmitter. Then, 1 meter up to a distance of 10 meters from the transmitter and finally 2 meters until the end of the run (Fig. 2). This non-equal sampling rate is justified by the data analysis of next section, and it is due to the log-distance decay of the power; in order to perform a detailed analysis of the measured data, more measurement points are required at short distances.

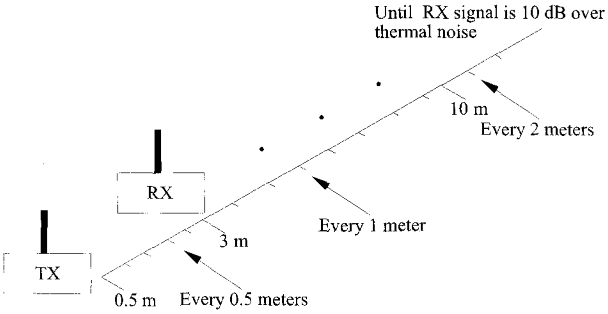


Fig. 2. Measurement methodology.

Apart from the described spatial sampling (Fig. 2), in order to obtain an average value of the received power at each receiver position, a 5 samples spatial averaging over 50 cm (around the central position) and (for all these five positions) a 5 times time averaging have been performed (25 snapshots at each distance). Spatial averaging has been done in order to study fluctuations over the mean received power and time averaging to check the time invariance assumption. It has been observed that the received power did not change during the measurements, i.e., there were no moving objects in the environments and both the transmitter and the receiver remained static.

IV. RADIO CHANNEL MODEL

After collecting the data a preliminary analysis of the measurements was made. It was found that the average received power in logarithmic scale tends to a straight line using the method of least square errors (log-distance attenuation). This trend is illustrated in Fig. 3 where the results for one run in the first scenario according to the methodology explained above (time averaged received power) are shown. The same behavior was found in the other measurements and scenarios. In addition, there was a slightly fading (shadowing), that is, the received power randomly fluctuated around the average power. In radio propagation, a log-distance decay of the received power [17] is generally accepted. So, the first step was to consider a log-normal path loss model in order to characterize propagation.

However, the antenna heights are very low (less than λ), and

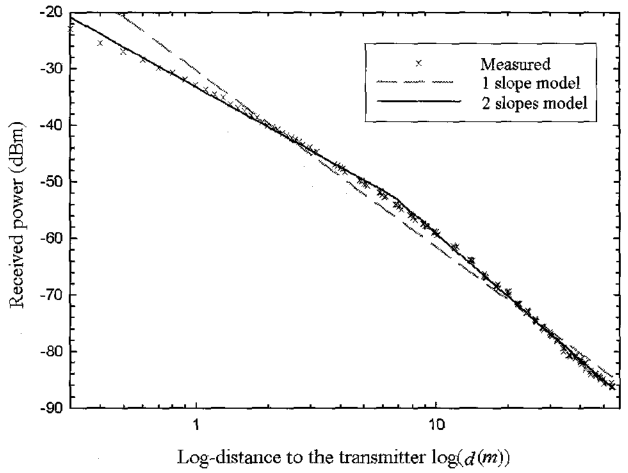


Fig. 3. Results for the ground plain scenario.

an important part of the Fresnel zone is always obstructed by the ground. The two-segment least-square fit line model is widely used to model propagation where part of the energy is intercepted by the ground. But the two slope model is not commonly used in near ground communications, and in particular in WSN. Therefore, this latter model was also used and at each scenario these two models are compared: A one slope log-distance path loss model and a two slope log-distance path loss model. The path loss [10] can be denoted by

$$L(d) = L_0 + 10n\log_{10}(d) + X_\sigma \qquad (1)$$

$$L(d) = \begin{cases} L_{01} + 10n_1\log_{10}(d) + X_{\sigma 1}, \text{ if } d \le d_r \\ L_{02} + 10n_2\log_{10}(d) + X_{\sigma 2}, \text{ if } d > d_r \end{cases} \qquad (2)$$

where in (1) L_0 is the path loss at 1 meter, n is the path loss factor, d is the distance expressed in meters, and X_σ is a lognormal variable with standard deviation of σ (in dB). In (2), two different slopes are defined before and after a breakpoint d_r. Fig. 3 shows the results for one run in the first scenario according to the methodology explained in the previous section. It can be observed that the received power fits a two slope model better than a one slope model, and this affirmation will be further checked latter. The same behavior is found in the other measurements at each scenario. From a certain distance from the transmitter, most of the energy is intercepted by the ground and this causes a greater decay factor in the path loss. For each measured environment, the two modes were applied to each run and all the results were averaged. They are summarized in Table 1 for each environment. The standard deviation is the residual error for both models, so it can be affirmed that a two slope model is a better characterization of radio propagation for near ground communications, i.e., a lower error (σ) is found.

An interesting observation found is that the breakpoint is environment dependent, and that it cannot be calculated as in [17], where it is said that it only depends on the antennas height (13 cm for this configuration) and the carrier frequency. Indeed, both the first and the second scenarios are flat but two different breakpoints were found. The park scenario was slightly curved, which explains the fact that the breakpoint becomes even closer to the transmitter (a bigger Fresnel zone is intercepted by the ground). In addition, in this model n_2 tends to 4, which is the expected value for a line of sight situation after the breakpoint if a two-ray ground reflection model is considered [17]. Considering a conventional free space model (n equals to 2) would lead to very large and unrealistic coverage areas. This attenuation coefficient is crucial for a simulator, because it fixes the maximum transmission range of a node. In Table 1, the maximum averaged radio coverage was calculated for a transmitted power of 5 dBm and a sensitivity of -100 dBm using both models, and it is concluded that the two slope model is more restrictive than the one slope model.

Table 1. Adjustment model parameters for the three scenarios.

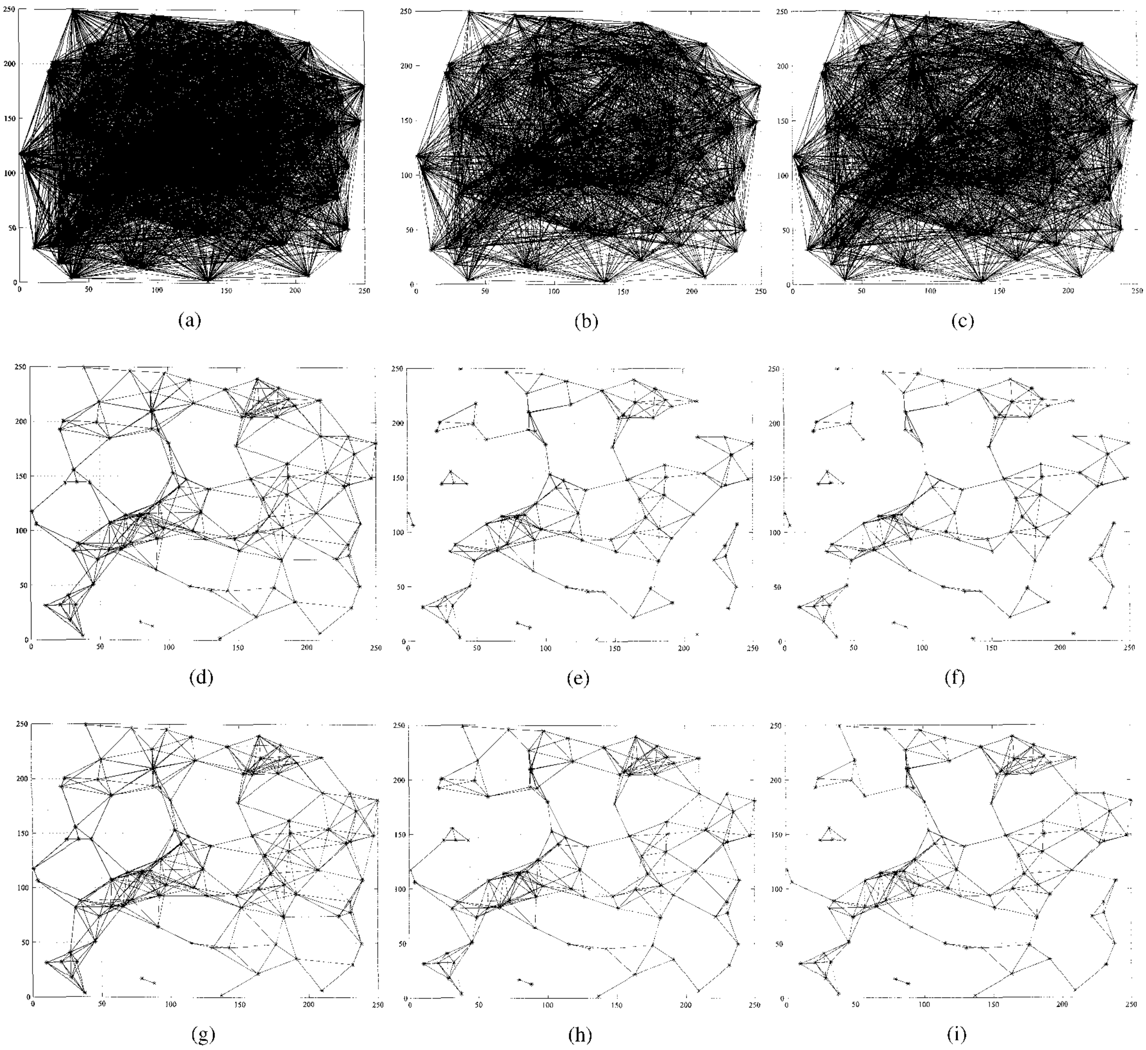
One slope	Ground plain	University yard	Park
n	3.12	3.57	3.69
σ	1.83	3.27	1.42
$d_{\max}$ (m)	172.53	41.26	42.83
Two slope	**Ground plain**	**University yard**	**Park**
n_1	2.34	2.76	2.09
n_2	3.73	4	4.01
σ_1	0.6	2.98	0.28
σ_2	0.42	1.82	0.67
Breakpoint (m)	6.2	3.2	0.95
$d_{\max}$ (m)	125	32.5	37.5

As stated in Section II, there is an increasing concern about unreliability of wireless links in WSNs due to stochastic behavior [13]. With the lognormal model, by means of the gaussian random variable component X_σ, an expression that models a normal random behavior can be easily implemented in a simulator. It should be noticed finally, that if real nodes antennas with a little ground plane (i.e., a poor and irregular radiation pattern) are used, the σ_{dB} may be bigger [14].

V. IMPACT OF RADIO MODEL ON SIMULATION PERFORMANCE

Our last step has been to check the impact on simulation results in order to validate our assumption regarding the computational cost of our models.

As mentioned in Section II, simulation results depend on radio channel model. The reason behind this is that the network connectivity is given by the radio model in wireless networks. Differences in connectivity have an influence on almost every layer of the communication stack. For instance, performance of contention-based medium access protocols depends on the number of neighbors (contenders). Many routing protocols are designed on the basis of an exact knowledge of one hop neighbors. However, network connectivity is usually overestimated by simpler models as free space. Therefore, we have first tested the influence of our different models in network connectivity . For all scenarios, we have placed 100 nodes randomly (with uniform distribution) over an area of 250×250 m^2. Fig. 4 shows the links between nodes when transmitting with 5 dBm of transmission power and a sensitivity of -100 dBm (typical for the



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 4. Network connectivity for a 100 node uniform topology with two different models and the real measurements in three scenarios: (a) Plain 1 slope, (b) plain 2 slopes, (c) plain real, (d) university 1 slope, (e) university 2 slopes, (f) university real, (g) park 1 slope, (h) park 2 slopes, (i) park real.

Table 2. Average percentage of neighbors per node.

Scenario	One slope	Two slope	Real
Plain	0.77	0.51	0.50
University	0.075	0.046	0.044
Park	0.08	0.061	0.052

Mica2 transceiver [15]). Network connectivity in these pictures has been computed just with the deterministic part of the models (the path-loss component). That is, no normal random variate has been added. In order to compare both models with the real data at any distance, in Figs. 4(c), 4(f), and 4(i), we have interpolated the real measurements using splines [18].

To complete the explanation, Table 2 shows the average number of neighbors in range per node, expressed as the ratio of the actual number of links to the total number of links possible ($N \times (N-1)$, being N the number of nodes).

In the ground plain scenario, the one slope model produces an unrealistic value of the mean number of neighbors (70 nodes). The two slope model achieves, however, a closer value to the one predicted with real measurements. Still it is too high. This high degree of network connectivity is due to the fact that the plain scenario is a quasi-ideal flat place and it tends to a free-space situation. It should also be remarked that the free-space propagation for the three scenarios is quite unrealistic with a coverage radio of more than 4000 m (i.e., full network connectivity).

Let us notice how the parameters of the model have a strong influence on the results. Comparing the network connectivity degree and number of neighbors between the ground plain and the university and the grass park, it can be seen that results are quite different (an order of magnitude). It shows that the selection of appropriate parameters is crucial.

An important result appears in the university and park scenarios: The one slope model also overestimates network connectivity, despite being considered a realistic model and being widely used. However, Figs. 4(d) and 4(g) show more links than the real (interpolated) data in Figs. 4(f) and 4(i). It has been demonstrated, hence, that the two slope model is more accurate.

Finally, we have tested the computational cost of the models. We have implemented the one slope and the two slope log-

Table 3. Computational speed of models.

Model	Speed	Ratio
One slope log-normal	258.39×10^3 comp/s	1
Two slope log-normal	257.07×10^3 comp/s	0.99
Linear interpolation	222.22×10^3 comp/s	0.86

normal model in a simple program written in C. This program computes propagation losses continuously for diferent distances in a 10^8 iteration loop. We have measured the time needed to perform this loop. To compare with a more realistic model implementation, we have also computed propagation losses by linear interpolation of our real data. Let us note that this kind of interpolation is less accurate but quite faster than spline interpolation. Table 3 shows the number of propagation computations per second (on a 1.2 GHz P-IV, under Linux). As it can be seen, the two slope model is slightly slower than the one slope model, but just a 1% slower, which is negligible. Therefore, we can conclude that the two slope model has a computational cost similar to the commonly used one slope log-normal.

VI. CONCLUSIONS

Multiple research papers in the field have presented simulation results for WSNs. The majority of these works rely on simplistic physical layer assumptions of channel models that can lead to mistaken results. Most of the envisioned applications for WSNs consider that the nodes are lying on the ground. To the best of our knowledge, there are no experimental studies that validate a radio channel model at the near ground level for WSNs. In this paper, we present the results of several measurement campaigns that validate a two slope log-normal path-loss model at 868 MHz. The second slope appears because the antennas are just a few centimeters over the ground and an important part of the Fresnel zone is always intercepted by the ground. It has also been shown that the breakpoint (the distance of change between the first and the second slope) depends on the environment and it does not agree with the breakpoint commonly used in the scientific literature for higher antenna locations. Furthermore, the exponent for near field path loss is almost always assumed to be 2.0 (free space), but the measurement data show that it is not actually the case.

In addition, we demonstrate that the two slope log-normal channel model achieves a realistic and more accurate propagation characterization than the one slope model.

Model parameters for propagation in different scenarios (ground plain, university yard, grass park) are also computed. They can be used to configure propagation model parameters for WSN simulation. With these experimentally derived parameters, the two slope lognormal model provides improved accuracy and it does not increase computational cost, being suitable for large scale WSN simulations, which allows to obtain more reliable results and conclusions about protocol and network performance.

Finally, we conclude that a correct study and analysis of sensor placement and coverage must take a proper radio propagation model into consideration with adjusted parameters for a target scenario.

ACKNOWLEDGMENTS

This work has been funded by the Economy, Industry and Innovation Council, from the Region of Murcia, with the SOLIDMOVIL project (2I04SU044) and supported by Fundacion Seneca, from the Region of Murcia, with the ARENA Project (00546/PI/04).

REFERENCES

[1] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, "An analysis of a large scale habitat monitoring application," in *Proc. ACM SenSys 2004*, Baltimore (USA), Nov. 2004.

[2] D. Ganesan, D. Estrin, A. Woo, and D. Culler, "Complex behavior at scale: An experimental study of low-power wireless sensor networks," Technical Report UCLA/CSD-TR02-0013, Center for Embedded Networked Sensing, University of California, Berkeley, Feb. 2002.

[3] E. Egea-López, J. Vales-Alonso, A. S. Martínez-Sala, P. Pavón-Mariño, and J. García-Haro, "Simulation tools for wireless sensor networks," in *Proc. SPECTS 2005*, Philadelphia, PA, July 2005, pp. 559–566.

[4] D. Kotz, C. Newport, B. Gray, J. Liu, Y. Yuan, and C. Elliot, "Experimental evaluation of wireless simulation assumptions," in *Proc. ACM/IEEE MSWiM 2004*, Venice, Italy, Oct. 2004, pp. 78–82.

[5] M. Takai, R. Bagrodia, K. Tang, and M. Gerla, "Efficient wireless network simulations with detailed propagation models," *Wireless Networks*, vol. 7, no. 3, pp. 297–305, May 2001.

[6] V. Naoumov and T. Gross, "Simulation of large ad-hoc networks," in *Proc. ACM MSWiM 2003*, San Diego, CA, 2003, pp. 50–57.

[7] The network simulator ns-2, http://www.isi.edu/nsnam/ns/.

[8] L. F. Perrone, Y. Yuan, and M. Nicol, "Modeling and simulation best practices for wireless ad hoc networks," in *Proc. 2003 Winter Simulation Conf.*, New Orleans, LA, 2003, pp. 685–693.

[9] K. Sohrabi, B. Manriquez, and G. Pottie, "Near-ground wideband channel measurements," in *Proc. IEEE VTC'99*, New York, 1999, pp. 571–574.

[10] T. Rappaport, *Principles of Communications Systems*, Prentice Hall, 2nd ed.

[11] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor networks," in *Proc. ACM SenSys 2003*, Los Angeles, California (USA), Nov. 2003.

[12] A. Woo, T. Tong, and D. Culler, "Taming the underlying issues for reliable multihop routing in sensor networks," in *Proc. ACM SenSys 2003*, Los Angeles, California (USA), Nov. 2003.

[13] N. Reijers, G. P. Halkes, and K. G. Langendoen, "Link layer in sensor networks," in *Proc. IEEE Int. Conf. Mobile Ad-hoc and Sensor Systems 2004*, Florida (USA), Oct. 2004.

[14] G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic, "Impact of radio irregularity on wireless sensor networks," in *Proc. MobySys 2004*, Boston, MA, June 2004, pp. 125–138.

[15] Chipcon CC1000, http://www.chipcon.com.

[16] Mica2 MOTES, http://www.xbow.com.

[17] H. L. Bertoni, *Radio Propagation for Modern Wireless Systems*, New Jersey, Prentice Hall, 2000.

[18] H. Späth, *One Dimensional Spline Interpolation Algorithms*, Wellesley, A. K. Peters Ltd., 1995.

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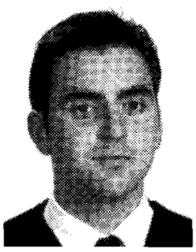

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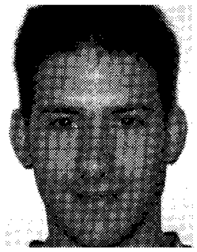

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