Empirical Path Loss Models for Wireless Sensor Network Deployment in Snowy Environments

Michael Cheffena and Marshed Mohamed

***Abstract*—In this paper, practical sensor nodes are utilized to study the path loss effects of wireless sensor networks (WSNs) at 2.425 GHz in a ground covered by snow at different heights from the ground. The measurement results are compared with the ground reflection (Two-Ray) path loss model and ray tracing model showing significant difference. New empirical path loss models for different heights from the ground based on the log-distance path loss model are presented. The developed models are compared with existing path loss models to demonstrate their accuracy between sensor nodes deployed in snowy environments. The experimental data as well as the developed path loss models can be utilized for efficient planning and deployments of WSNs in snowy environments. They can support applications including rescue and monitoring of snow avalanche, environmental surveillance or monitoring winter sporting activities.**

***Index Terms*—Path loss, wave propagation, channel model, snow avalanche, wireless sensor network, WSN.**

I. INTRODUCTION

IN the past few years, wireless sensor networks (WSNs) have been used in different applications including medical, industrial, agricultural and surveillance. The wireless nodes are deployed in a given area (with a specific link and network configuration) for collecting and transmitting/receiving sensor data. Successful design of such networks requires good understanding of the propagation impairments affecting the wireless links, among them is path loss. Path loss describes how the received signal power decreases with increasing distance between the transmitting and receiving nodes, and it depends on the type of environment the network is deployed. Path loss effects in environments covered with snow has not been extensively studied compared with studies in other environments such as open areas, road sides, grassy, forest, etc. This type of study is essential for efficiently deploying WSNs in different applications such as rescue and monitoring of snow avalanche, environmental surveillance or monitoring winter sporting activities.

Many different path loss models have been developed for various outdoor deployment of WSNs. Near-ground path loss radio frequency (RF) measurements on a tarmac surface similar to that of a roads is reported in [1]. Empirical path loss models for WSN deployments in short and tall natural grass and forest environments are reported in [2] and [3], respectively. Denis et al. [4] reported ultra wideband (UWB) measurement results and path loss modeling for snowy environments for rescue and monitoring of snow avalanche victim applications. Near-Earth wave propagation characteristics of electric dipole in the presence of vegetation and snow layer was considered in [5]. Experimental study of propagation characteristics on roads on a snowy mountain was conducted in [6]. Marfievici et al. [7] studied the effect of snow for large scale deployment of WSNs. Most previous studies in snowy environments use signal generators instead of practical sensor nodes, which in turn may lead to inaccurate models. This can be due to antenna mismatching as well as gain, directivity and pattern changes raised after practical WSN antennas are incorporated in to miniature radios. Resulting in poor decision making during large-scale deployment of WSNs in these environments. In accurate models may also lead to poor energy efficiency of the sensor nodes [8] as well as inaccuracy in localization and target-tracking applications [9]. Thus, accurate characterization of the propagation channel utilizing practical sensor nodes is required for large-scale deployment of WSNs in snowy environments.

In this work, practical sensor nodes are used to characterize the path loss effects of WSNs at 2.425 GHz in snowy environments at different heights from the ground. The measurement results are compared with the ground reflection (Two-Ray) path loss model and ray tracing model showing significant difference. New empirical path loss models for different heights from the ground based on the log-distance path loss model are developed. The models are compared with existing models to demonstrate their accuracy between sensor nodes deployed in snowy environments. The measured data as well as the developed path loss models can be used for efficient planning and deployments of WSNs in snowy environments.

The rest of the paper is organized as follows. Section II describes the measurement campaign, presenting the practical sensor nodes used and the investigated scenarios. Data analysis and the measurement results are discussed in Section III. Conclusions are given in Section IV.

II. MEASUREMENT SET-UP

Measurement campaign was conducted utilizing practical sensor nodes for characterizing the path loss effects of WSNs in snowy environments at different heights from the ground. The conceptual overview of the measurement campaign is shown in Fig. 1. The transmitter (Tx) was placed at a fixed position while the receiver (Rx) was moved following a straight trajectory, along which samples were taken at separation distances from 5 to 30 m with a step size of 5 m. Both the Tx and the Rx were mounted on a mass of equal heights above the ground. The measurements were repeated for three different heights from the ground i.e., 0.25 m, 1 m and 1.5 m. The measurements were taken in a large football field covered by snow, see Fig. 2.

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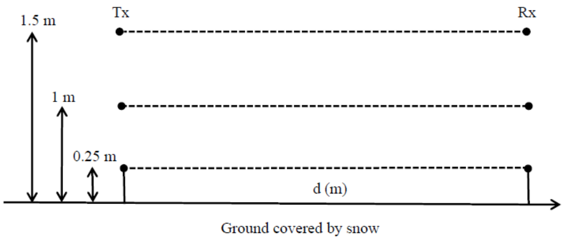

Fig. 1. Link configurations of the measurement campaign. The samples were taken at Tx-Rx separation distances from 5 to 30 m with a step size of 5 m for 0.25m, 1 m and 1.5 m heights above a ground covered by snow.

Fig. 2. Measurement site: a large football field covered by snow with Tx and Rx nodes mounted on a mass of different heights (0.25 m, 1 m and 1.5 m) from the ground.

The measurements were conducted using programmable radio transceivers with non-volatile data storage. The nodes comprise of a radio transceiver, antenna, microcontroller, microSD memory card and battery, see Fig. 3. The radio transceiver is CC2500 from Texas Instrument [10]. The Tx was set to transmit a packet every 4 ms with constant transmission power of 1 dBm at 2.425 GHz carrier frequency. At each location, the RX received packets for about 2 minutes before it is moved to the next location. The received signal strength indicator (RSSI) together with the packet number was stored on the MicroSD memory card of the RX node. The nodes use vertically polarized Wurth Electronik 7488910245 chip antenna. After completing the measurement campaign, the data was exported from the memory card of the RX node to a computer running a Matlab software for analysis.

Fig. 3. Practical sensor node for path loss measurements consists of a radio transceiver, antenna, microcontroller, microSD memory card and battery. Shown together with Norwegian one krone.

III. MEASUREMENT RESULTS AND ANALYSIS

A. Path loss models

The lower bond estimation of path loss can be obtained utilizing the free space path loss (FSPL) model given by

$$L_{\text{FSPL}}[\text{dB}] = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \tag{1}$$

where d is the Tx-Rx separation distance (in meters) and λ is the wavelength. For near-ground propagation, the path loss can be estimated using the plane Earth wave propagation model instead of the FSPL model. The model takes into account the effect of ground reflected ray as well as the line-of-sight (LOS) ray. Rappaport [11] showed how the calculation of the interference between the LOS and reflected rays can be simplified for large distances as

$$L_{\text{GR}}[\text{dB}] = 20\log_{10}\left(\frac{d^2}{h_t h_r}\right) \tag{2}$$

where parameters h_t and h_r are the Tx and Rx heights above the ground in meters, respectively. This has lead to the development of the Two-Ray ground reflection path loss model which utilizes a cross-over distance where the path loss from (1) and (2) breaks even, expressed as [12]

$$L_{\text{two-ray ground PL}}[\text{dB}] = \begin{cases} L_{\text{FSPL}}[\text{dB}], & \text{if } d \le d_c \\ L_{\text{GR}}[\text{dB}], & \text{if } d \ge d_c \end{cases} \tag{3}$$

where parameter d_c is the cross-over distance defined as

$$d_c = \frac{4\pi h_t h_r}{\lambda} \tag{4}$$

In most cases, the path loss for the same Tx-Rx distance might be different due to multipath effects, terrain (location) variations and other effects. If these effects are considered, (1) becomes as shown in (5), commonly known as the log-distance path loss model [11]

$$L_{\text{LG}}(d)[\text{dB}] = L(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma \tag{5}$$

where n is the path loss exponent, which shows the rate at which the received signal power decrease with distance and $L(d_0)$ is the path loss in dB at a reference distance, d_0. Parameter χ_σ is a zero-mean Gaussian random variable with standard deviation $\sigma(\text{dB})$ when expressed in dB scale, and describes the shadowing effects. Parameters $L(d_0)$ and n can be estimated by performing linear regression with the measurement data. While $\sigma(\text{dB})$ may be determined from experimental data using [2]

$$\sigma(\text{dB}) = \sqrt{\sum_{i=1}^{N}\frac{\left(L_{\text{meas}}(i) - L_{\text{pred}}(i)\right)^2}{N-1}} \tag{6}$$

where $L_{\text{meas}}(i)$ and $L_{\text{pred}}(i)$ are the measured and predicted average path loss at point i, respectively. Parameter N is the total number of path loss samples.

A ray tracing approach can also be used for calculating path loss values taking into account possible propagation paths (direct and ground reflected) and the dielectric property of ice with relative permittivity and conductivity equal to 3 and 5×10^{-4}, respectively [13].

B. Measured values

Figure 4 shows the path loss measurements against distance for the case when the nodes are 0.25 m, 1 m and 1.5 m above the ground. As expected the path loss increases with increasing Tx-Rx separation distance. The high path loss observed at the height of 0.25 m compared with the rest of the antenna heights is due to the link being in the first Fresnel zone at this height (the first Fresnel zone radius at 5 m Tx-Rx separation distance is 0.39 m and increases to 0.96 m at Tx-Rx separation distance of 30 m). As for the 1 m and 1.5 m heights, the difference in path loss arises due to the constructive and destructive summations of the LOS ray and the ground reflected ray. For example, at 15 m distance where we observe the largest path loss for the 1 m height, the main ground reflected ray has a phase shift of around 1.16π, resulting in destructive interference with the LOS ray and hence high path loss. This is not the case for the 1.5 m height where the phase shift in the main ground reflected ray is around 1.85π resulting in constructive interference with the LOS ray instead.

Figs 5 to 7 show comparisons between the measured and the theoretical path loss models discussed above for 0.25 m, 1 m and 1.5 m heights above the ground, respectively. The corresponding values are also given in Table I. For the log-distance model given in (5), the path loss exponent, n, and $L(d_0)$ are obtained by performing linear regression on the measurement data. For the 1 m height above the ground data set, the outlier found at Tx-Rx separation distance of 15 m (see Fig. 4) was not included in the regression analysis. The parameter $\sigma(\text{dB})$ is estimated using (6). The value of the regression coefficients and the statistical results of the regression for different heights above the ground are shown in Table II. The critical values for at least 95% significance for the F-statistics together with the P-values are also presented in Table II. The standard error of the regression (predicted minus measured) indicates the goodness of fit. The statistical significance of the regression is indicated by the F-statistics and the multiple determination coefficient R^2. The higher the value of the F statistic comparing to the critical value of 95% confidence, the more statistically significant is the regression. This is also true the closer R^2 gets to 1. We can clearly observe from the statistical results of Table II that the regression path loss models are statistically significant.

The prediction errors of the log-distance model, the Two-Ray ground reflection model, and the ray tracing model were also calculated in order to evaluate and compare their performance. Table III shows the mean, standard deviation, and the root mean square (RMS) error of the three models. In all cases, we can observe that best prediction is achieved using the log-distance path loss model.

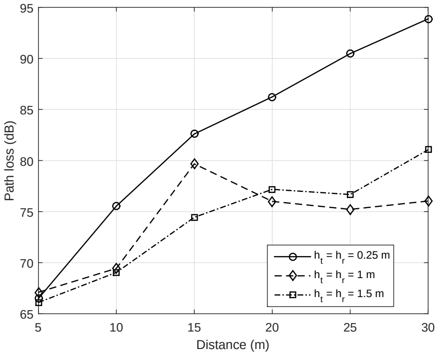

Fig. 4. Path loss measurement results of sensor nodes for 0.25 m, 1 m and 1.5 m heights above the ground covered by snow.

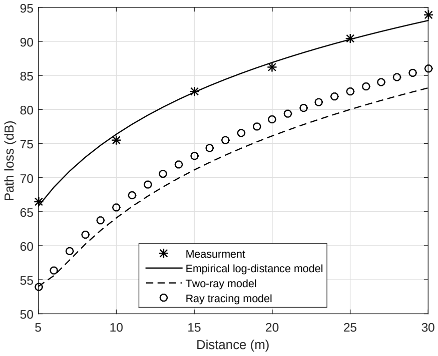

Fig. 5. Measured and theoretical path loss models for 0.25 m height above the ground covered by snow. The cross-over distance d_c is equal to 6.3 m thus the first Fresnel zone is not cleared. The two-slope decay fitting is done for the Two-ray model using (3).

IV. CONCLUSIONS

WSNs in snowy environments can support applications such as rescue and monitoring of snow avalanche, environmental surveillance or monitoring winter sport activities. Large-scale deployment of WSNs in snowy environments require accurate characterization of the propagation channel utilizing practical sensor nodes. However, most existing studies in snowy environments use signal generators instead of practical sensor nodes, which in turn may lead to inaccurate models, and as a result poor decision making during large-scale deployment of WSNs. In accurate models may also result in poor energy efficiency of the network as well as inaccuracy in localization and target-tracking applications.

In this work, empirical path loss models for WSN deployment in snowy environments at different heights are developed using practical sensor node measurements at 2.425 GHz. The

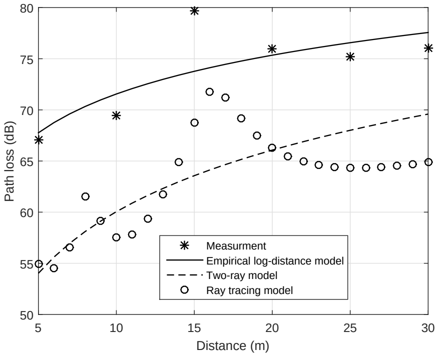

Fig. 6. Measured and theoretical path loss models for 1 m height above the ground covered by snow. The cross-over distance d_c is equal to 100.5 m thus the first Fresnel zone is cleared. The Two-ray model is plotted using (1).

TABLE I

AVERAGE PATH LOSS (dB) AT A 5-M INTERVAL FOR DIFFERENT HEIGHTS FROM THE GROUND

Average path loss		Distance (m)					
Height (m)	Method	5	10	15	20	25	30
0.25	Measurement	66.49	75.54	82.60	86.24	90.47	93.87
	Empirical log-distance model	65.83	76.37	82.53	86.90	90.29	93.07
	Two-Ray model	54.03	64.08	71.13	76.12	80	83.17
	Ray tracing model	53.98	65.66	73.16	78.50	82.63	86.01
1	Measurement	67.10	69.44	79.67	76	75.22	76.06
	Empirical log-distance model	66.76	71.55	73.77	75.35	76.57	77.56
	Two-Ray model	54.03	60.05	63.57	66.07	68	69.59
	Ray tracing model	54.95	57.52	68.74	66.28	64.35	64.87
1.5	Measurement	66.10	69.05	74.44	77.18	76.67	81.06
	Empirical log-distance model	65.16	70.79	74.08	76.42	78.23	79.71
	Two-Ray model	54.03	60.05	63.57	66.07	68	69.59
	Ray tracing model	54.13	58.35	61.03	66.64	64.15	69.29

TABLE II

PATH LOSS REGRESSION COEFFICIENTS AND STATISTICAL RESULTS

Height (m)	$L(d_0)$[dB]	n	σ(dB)	Error variance	F-critical	F-statistic	P-value	R^2
0.25	65.83	3.51	0.67	0.56	7.71	914.95	0	1
1	66.76	1.26	2.97	1.50	10.13	44.02	0	0.94
1.5	65.16	1.87	1.33	2.22	7.71	65.45	0	0.94

TABLE III

PREDICTION ERRORS OF THE LOG-DISTANCE, TWO-RAY GROUND REFLECTION, AND RAY TRACING PATH LOSS MODELS

Height (m)	Model	Mean	Std	RMS
0.25	Empirical log-distance model	0.04	0.67	0.61
	Two-Ray model	11.11	0.85	11.14
	Ray tracing model	9.21	1.86	9.37
1	Empirical log-distance model	0.32	2.94	2.70
	Two-Ray model	10.36	3.64	10.88
	Ray tracing model	11.13	0.87	11.16
1.5	Empirical log-distance model	0.02	1.33	1.22
	Two-Ray model	10.53	1.38	10.61
	Ray tracing model	11.82	1.09	11.86

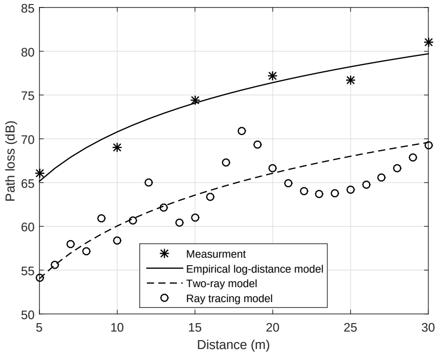

Fig. 7. Measured and theoretical path loss models for 1.5 m height above the ground covered by snow. The cross-over distance d_c is equal to 226.2 m thus the first Fresnel zone is cleared. The Two-ray model is plotted using (1).

results are compared with the Two-Ray ground reflection and ray tracing path loss models showing significant deviations. New empirical models based on the log-distance path loss model for different heights are developed and compared with existing path loss models to demonstrate their accuracy between sensor nodes deployed in snowy environments.

The measured data as well as the proposed models can be useful for efficient planning and deployment of WSNs in snowy environments.

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