A Ground Level Radio Propagation Model for Road-based Wireless Sensor Networks

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***Abstract*— this paper investigates the use of a wireless sensor network (WSN) for communicating between road-based nodes. These nodes are situated at ground level and two-way wireless communication is required between the nodes and from the nodes to a roadside control unit. Measurements have been carried out to examine the propagation close to the ground to determine the maximum distance between road-based nodes as a function of the antenna height. The results show that for a frequency of 2.4 GHz, a range of up to 8m is achievable with 2mW EIRP. An empirical near-ground level radio propagation model is derived and the predicted results from this model are shown to match closely to the measured results.**

***Keywords*— Radio propagation model; ground level; wireless sensor networks**

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a collection of low-power nodes, each with a radio transceiver that allows wireless communication between the nodes. Such WSNs can be used in various systems such as energy monitoring [1], automation [2], hospital/patient management systems [3] and Intelligent Transportation System (ITS) [4, 5]. This paper investigates the use of wireless sensor technology for communicating with road-based nodes, with a specific focus on radio propagation at ground level.

Road-based sensors are used for monitoring traffic and providing information for traffic control systems. Current systems generally use wire loops for sensors and these are cabled to a roadside control unit. The disadvantage of these systems is that the cabling can be costly to install and can weaken the road surface. An alternative is to use wireless technology to provide connectivity and so avoid the need for cables. Recently, road-based sensors have been introduced which include LED lighting for lane marking [6]. These road studs are battery powered with a solar cell to charge the battery. They are easy to install and minimise the disruption of the road surface. The aim of this paper is to investigate the feasibility of extending the capability of these low-powered nodes by including a wireless transceiver to allow them to communicate between other road-based nodes and to a roadside control unit without the need for cables in the road. A wireless network installed in a road environment presents a significant challenge because signal propagation between the sensors on the ground will be partially obstructed by the road surface and by passing vehicles [5]. In addition the available battery capacity and the solar cell charging capability will limit the amount of power available for data transmission and sensor data processing.

This paper studies radio propagation at ground level at a frequency of 2.4 GHz. The relationship between the radio signal path loss and the distance between nodes is investigated as a function of the height of the nodes. Field measurements are carried out at different heights and an empirical radio propagation model is derived to match the measurements.

The paper is structured as follows: Section I is an introduction. Section II provides a review of the literature on near ground level propagation studies. Our experimental environment and the field measurement results are presented in Section III. Section IV proposes a near-ground radio propagation model and Section V concludes the paper.

II. RELATED WORK

The effects of antenna height on path loss propagation near to the ground have been investigated in [7-12].

In [11], Stoyanova *et al* carried out some measurements in an outdoor environment with sensors deployed at heights of 12 cm, 70 cm, 150 cm and 197 cm for both the transmitter and the receiver. The sensors used are Tmote Sky sensor nodes, which have 2.4GHz CC2420 radio modules with internal omnidirectional antennas. The results of this study show that when the antenna height decreases, the path loss increases. The paper proposes a propagation model based on combining the free-space path loss and the plane earth propagation models and including factors to account for ground reflection and antenna pattern irregularity:

$$\bar{P}_R(d) = P_T(\frac{\lambda}{4\pi d})^2(K_1^2 + K_2^2\Gamma^2 + 2K_2\Gamma\cos(\frac{2\pi}{\lambda}\Delta L)) \quad (1)$$

where P_R is the received power, P_T is the transmission power, d is distance between the transmitter and receiver, λ is the wavelength, L includes transmission lines, antenna losses, ΔL is the path difference between the direct and the reflected rays, K_1 and K_2 represent the antenna gain and Γ the ground reflection coefficient.

$$P_R(d) = \overline{P_R}(\mathrm{d}) + X_{\sigma(\overline{P_R})} \quad (2)$$

Equation (2) shows the Received Signal Strength (RSS) distribution as a Gaussian random variable X with standard deviation σ.

Equation (1) is a combination of the Free Space (FS) and Ground Reflection (GR) models. The results are compared with the Free space Outdoor Model (FOM) and the Long-distance Path Loss Model (LPLM). They found that FOM is capable of predicting the received signal strength (RSS) as a function of distance with greater accuracy than LPLM [11]. The results showed that the maximum range for FOM and LPLM for antenna heights of 0.12 m, 0.70 m and 1.50 m are 30 m, 65 m and 70 m respectively [11].

Janek *et al* [12] investigate the RF propagation for a WSN designed to operate in agricultural crop fields to collect aggregate data composed of subsurface soil moisture and soil temperature. This study shows that the effect of antenna placement close to the ground (within 10 cm) significantly changes the omnidirectional transmission pattern. A propagation model is proposed that includes an environmental propagation factor, the value of which is obtained by measurements in different environments, to test the reflection and absorption with and without obstacles. The proposed method takes into account environmental properties for RF communication range based on the height of nodes and gateways. To study the separation space between transmitter and receiver, it concentrates on the Fresnel zone effect for sensors located close to ground level. As the sensor gets closer to the ground, the propagated wave is affected by ground obstacles which lead to reflection and diffraction. These effects have been studied and analysed to produce a model that is able to predict the loss close to the ground surface. The proposed model considers the environmental factors and then uses this together with the free space model.

Their model considers a factor for each environment to be calculated with modified Friis equation which considers antenna height by use Golio and Goldsmith analytical treatments [12].

The environment factor $P_{(env)}$ is produced by measuring the difference $P_{r(diff)}$ between the expected power received $P_{r(exp)}$ (which is -98 dBm base on the receiver sensitivity) and the measured power $P_{r(meas)}$. This process is repeated for each environment, and then the differences between the $P_{r(exp)}$ and $P_{r(meas)}$ is classified based on the environment to be the propagation factor $P_{(env)}$ for each environment. Their model is defined as:

$$P_r = P_t + 10\log(G_t G_r) + 20\log(h_t h_r) - 40\log(d) - P_{\mathrm{env}} \quad (3)$$

where

$$P_{r(diff)} = P_{r(exp)} - P_{r(meas)}$$

and

$$P_{r(meas)} = P_t + 10\log(G_t G_r) + 20\log(h_t h_r) - 40\log(d) \quad (4)$$

where $P_{(exp)}$= -98 dBm

They performed field measurements at a university agriculture research facility. Three different test fields were studied: bare (not planted or tilled) soil, soybeans, and corn. Tests were performed where the transmitting node height (h_t) was 82.5 cm, 66 cm, 50 cm, 33 cm, 16 cm and 8 cm above the ground, at a frequency of 900MHz. For all crop environments, the receiver antenna was at a height of 0 m for at least a few centimetres, before the receiver antenna had to be raised. Each transmitter height has been tested to find out what the minimum receiver height to reach maximum range on different field. For example the maximum range for a transmitter height (h_t) and receiver height (h_r) of 8 cm is 6 m, and this range increases to 30 m when h_r and h_t are 1.2m. For h_t = 88.2cm and 66 cm, the required receiver height to reach 30 m are h_r = 18 and 20 cm, respectively.

The experimental results agree with the hypothesis that the antenna proximity to the ground plays a significant role in limiting the RF range. Test results from simulations, anechoic chamber measurements, and field experiments all indicated that as the height of an omnidirectional monopole antenna approached a ground plane, its radiation pattern changed.

A statistical model is proposed by Wang *et al* [7] for near-ground channels based on extensive measurements. One-slope and Two-slope models have been used to verify the measured results and compared with generic model.

$$L(d_i) = L(d_0) + 10n\log_{10}(d_i/d_0) + \varepsilon_i, \quad i=1,2,....,m \quad (5)$$

$$L(d_i) = \begin{cases} L(d_b) + 10n_1\log_{10}\left(\frac{d_i}{d_b}\right) + \varepsilon_{1i},\ d_i \leqslant d_b \\ L(d_{b+1}) + 10n_2\log_{10}\left(\frac{d_i}{d_b}\right) + \varepsilon_{2i}, d_i > d_b \end{cases} i = 1,2,m \quad (6)$$

In (5) d_0 is a reference distance close to the transmitter, and L (d_0) is the path loss value at d_0. In equation (6), two different slopes are defined before and after a breakpoint given by $d_i = d_b$ which is determined by measurements close to the transmitter. Where d_i is the selected point to measure and d_b is the breakpoint distance.

The $L(d_b)$ and $L(d_{b+1})$ are selected as the reference path losses before and after the breakpoint, respectively. For the two models, n, n_1, and n_2 are the path loss exponents which indicate the attenuation rate; ε_i, ε_{1i}, and ε_{2i} are a set of zero-mean random variables with standard deviation σ, σ_1, and σ_2, respectively.

Three different outdoor environments were selected in this work, including a large plaza, a straight sidewalk, and open grassland. At each of these three sites, the same methodology was applied at the same frequency 2.4 GHz. The transmitter position was fixed with antenna heights of 3 cm and 1m, and receiver antenna heights of 1 and 2m were used. Along the straight line followed by the receiver, the samples were collected every meter in a distance of up to 10 meter from the transmitter, and then every 2m until the end. It was found that the predicted values are in good agreement with the measured values. In [7], the maximum range and minimum antenna height achieved is 351m when the transmitter height is 3 cm and receiver height is 1 m in the Plaza environment. When the radio wave propagates near the ground with a line-of-sight (LOS) condition, the path loss can be better described by the plane-earth (PE) path loss model rather than the free-space model (explain why this is the case near to the ground. The plane-earth path loss model includes antenna heights and the effect of ground reflection [13]. It produces the closest result to measured results, but it is still unable to predict the path loss accurately, especially when the antenna is on ground level.

In the reported works described above, the minimum height of the antenna was 12 cm for the measurements at 2.4 GHz and 8 cm for the measurements at 900 MHz.

For the road-based node network proposed in this paper, antenna heights closer to the ground are needed, and in the next section measurements of the range for heights below 12.5 cm are described.

III. PROPAGATION MEASUREMENTS

A. Measurements

This section describes our work carried out to determine the effect of antenna height on the communication range for antenna heights in the range of 0~12.5 cm and using a frequency of 2.4 GHz. A frequency of 2.4 GHz is preferred for this application because the antenna needs to be small enough to fit into a road stud. An Arduino microcontroller with an XBee shield was used for the wireless transceivers. The effective isotropic radiated power (EIRP) of the transmitter power is 2mW.

To increase the antenna gain in the direction of the receiver a printed circuit board directional Yagi with a gain of 8.5 dBi, has been used (see Fig. 1a).

(a)

(b)

Figure 1: (a) Fabricated Xbee module with PCB Yagi located at ground level & (b) 2 Xbee module communicate on 2.5 cm over 2 m distance.

The measurements are carried out on a tennis court of the Oxford Brookes University Wheatley Campus. This has a tarmac surface similar to that of a road. Different antenna heights have been tested to study the effect of antenna height on path loss.

Measurements have been carried out at heights of 0 cm, 2.5 cm, 5 cm, 7.5 cm, 10 cm and 12.5 cm. The transmitter and receiver were at the same height (see Fig. 1b).

B. Results

The results of these measurements of received power as a function of node separation and antenna height are shown in Fig. 2. The minimum height is 0cm, i.e. ground level, by placing the printed antenna on the ground.

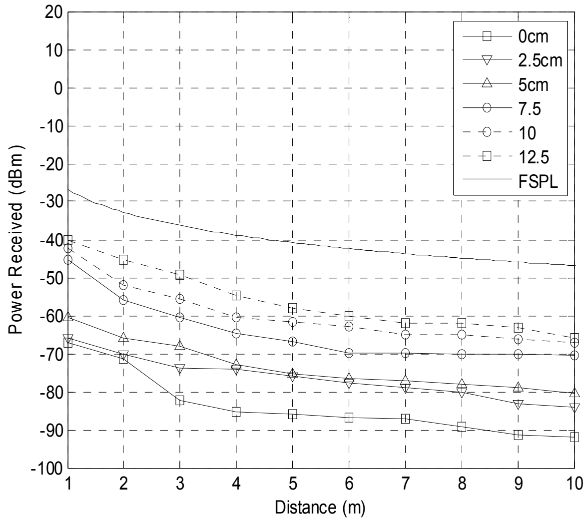


Figure 2: Measurements Result on Different Heights (Transmitter EIRP = 3 dBm)

The results show that the received power decreases with distance and also with decreasing height. The minimum received power for the Zigbee receiver is -92 dBm, so the maximum range for the antenna at ground level is about 9 m. This indicates that the communication on ground level is possible with minimum transmitted power as in sensors cases, also the maximum range can be achieved by using a directional antenna which concentrates its beam in a specific direction. However, at height 12.5 cm and at 1 m distance the value of received power is the closest to free space value, so that show the capability for this node to communicate more than 10 m easily.

The measurement results shown in Fig. 2 are also compared with Free Space Path Loss model (FSPL).

To analyse the variation of received power as a function of height, the results have been re-drawn as shown in Fig. 3. This graph shows received power recorded as a function of the antenna height for distances of 3 m, 5 m and 8 m, and it shows how the received signal strength increases with antenna height.

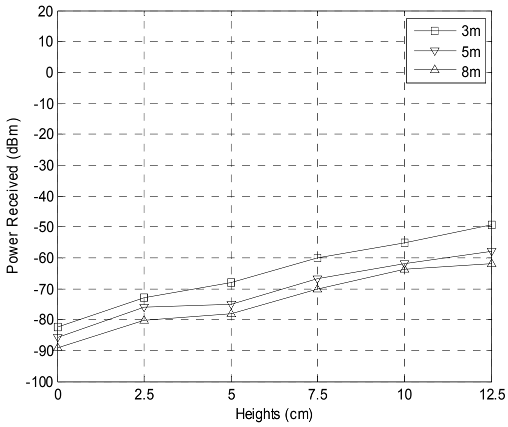


Figure 3: The effect of antenna height (Transmitter EIRP = 3 dBm)

IV. Proposed Propagation Model

The proposed empirical propagation model is derived from the FSPL model [14] with an adjustment factor to take account of the antenna height and the blocking effect of the ground.

The FSPL model, modified to include the gain of the transmitter and receiver antennas is given by:

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2} \qquad (7)$$

where P_r, P_t are the power at the receiver and the transmitter respectively; G_t, G_r are the corresponding antenna gains; λ is the radiation wavelength; and d is the distance between the transmitter and the receiver.

For antennas placed very close to the ground, the FSPL model is modified by a blocking factor (F) as shown in equation (8).

$$P_r = P_t \left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right).F \qquad (8)$$

Assuming the transmitter and receiver heights are equal, the blocking effect of the ground (F) increase is a function of the ratio of the height of the antenna (h) and the distance (d) between the transmitter and receiver. The blocking factor is modelled by a factor (F) as shown in equation (9).

$$F = \left(\frac{h}{d}\right)^n \qquad (9)$$

where the exponent n determines the magnitude of the blocking.

The overall propagation model is the Friis equation multiplied by the blocking factor in (9), as shown in (10).

$$P_r = P_t \left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right).\left(\frac{h}{d}\right)^n \qquad (10)$$

This model has been matched to the measured results using curve fitting and the values predicted by the model are shown in Fig. 4. The antenna gain is assumed to be $G_t = G_r = 4.5$. The value of n for each height is given in Fig. 5. It can be seen that the value of n is a function of height. The parameter n has therefore been modelled as shown in (11).

$$n = A\,h^3 + B\,h^2 + C\,h + D \qquad (11)$$

where h is the height of the antenna and A, B, C and D are constants.

Using curve fitting, the optimum values for the constants have been found to be:

$A = -0.0096$, $B = -0.1485$, $C = 1.1904$, $D = 12.591$

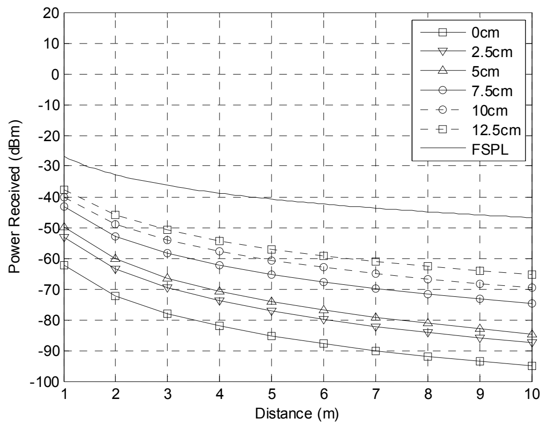


Figure 4: Results of proposed model (Transmitter EIRP = 3 dBm)

A. *Comparing the values predicted by the proposed model with the measurement results*

In Fig. 6: a, b, c, d and e the values of received power for a distance 1 m, 3 m, 5 m, 7 m and 9 m calculated using the proposed formula and these are compared with the collected results from the field measurements. It can be seen that there is a close match between the values predicted by the model and the measured values, which shows that the proposed model can provide an accurate prediction of the path loss for heights 0~12.5 cm which is the range of interest for the road-based wireless sensors.

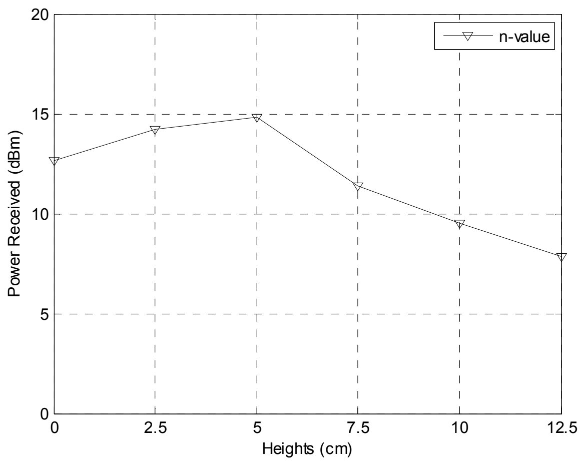
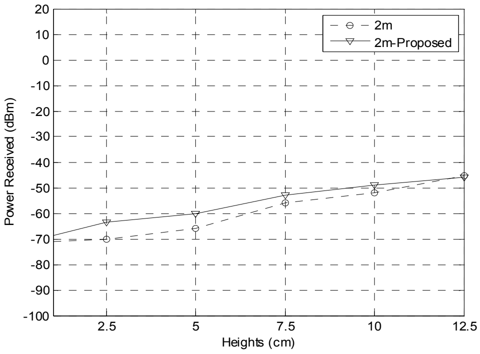
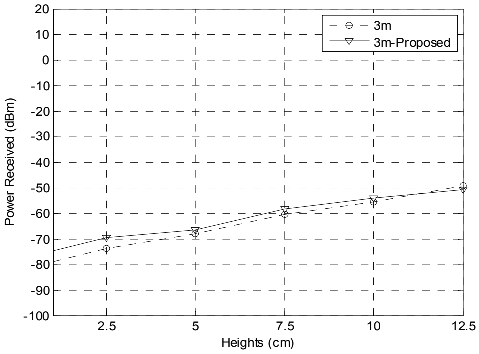


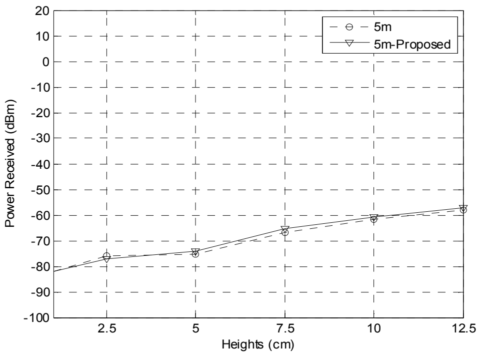
Figure 5: The n value for different heights (Transmitter EIRP = 3 dBm)



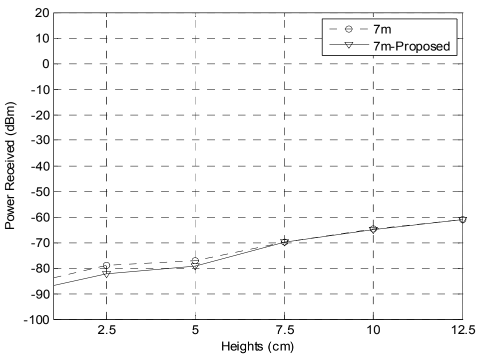
(a)



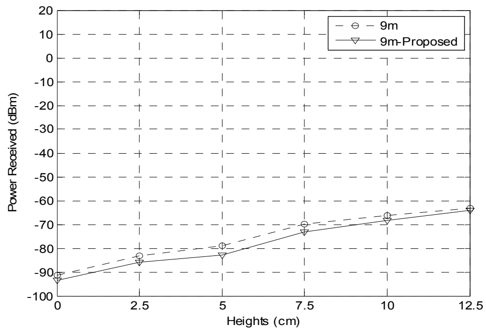
(b)



(c)



(d)



(e)

Figure 6: Compare the results of the proposed model and measurements results (Transmitter EIRP = 3 dBm)

B. *Comparing the proposed model with previously reported models*

In previous work [11, 12], the researchers proposed a propagation model for near ground level communication. The lowest antenna height for which results have been presented is 8.25 cm [12]. Fig. 7 compares the received power predicted by the Environmental Prediction Model (EPM) in [12] with the measured results and the model proposed in this paper for an antenna height of 7.5 cm. The results show that the model proposed in this paper provides a more accurate fit to the measured results than the EPM model in [12].

The EPM model in [12] uses an environmental factor which is based on soil as the ground surface whereas the results in this paper are based on a tarmac surface. This may explain the difference between the results.

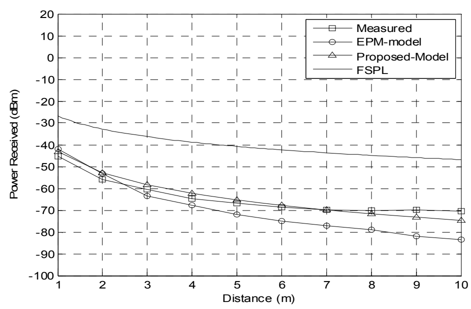


Figure 7: Comparison of the measured and modelled results in this paper with the values predicted by the EPM model in [12] at a height of 7.5 cm

Fig. 8 compares the received power predicted by the Free-Space Outdoor Model (FOM) presented in [11] with the measured results and the model proposed in this paper for an antenna height of 12.5 cms. The transmitter power used in [11] is 0 dBm, so the received power has been increased by 3 dB to make it comparable with the results in this paper which used a transmitter power of 3 dBm. The frequency is 2.4 GHz. The results show that the model proposed in this paper provides a more accurate fit to the measured results than the FOM model in [11].

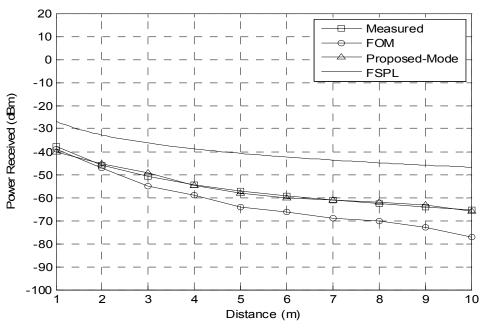


Figure 8: Comparison of the measured and modelled results in this paper with the values predicted by the FOM model in [11] at a height of 12.5 cm

Our proposed model therefore provides a more accurate prediction of the path loss for antennas placed close to a tarmac ground surface than previously reported results.

V. CONCLUSION

The aim of this work is to determine the viability of a wireless sensor network where the wireless transceivers are embedded in road studs located on the ground.

Previously, propagation measurements at a frequency of 2.4 GHz have been reported for antenna heights down to 8 cm above the ground but for the proposed application, the antennas will need to be lower than this. In order to determine the maximum separation of these nodes, measurements of propagation loss have been carried out for antenna heights of 0~12.5 cm and a node separation of 0~10 m. The measurements were carried out at a frequency of 2.4 GHz. A directional antenna has been used to improve the range. The measurements show that a range of up to 9 m is achievable for an antenna at ground level. This determines the maximum separation of the nodes in a tarmac surface, road-based wireless sensor network operating at a frequency of 2.4 GHz. An empirical model has been developed based on the measurement results, and this model is able to predict the path loss as a function of distance for antenna heights in the range 0~12.5 cm.

Further work is needed to investigate if the range can be improved by using alternative antenna designs. Similar measurements could also be carried out at lower frequencies such as 900 MHz to see if the range can be increased and the effect of different ground surfaces could also be analysed.

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