Path Loss Analysis of WSN Wave Propagation in Vegetation

Naseer Sabri¹, S A Aljunid¹, M S Salim², R Kamaruddin³, R B Ahmad¹, M F Malek¹
¹ Computer and Communication Engineering School, UniMAP, Malaysia
² Mechatronics Engineering School, UniMAP, Malaysia
³ Bioprocess Engineering School, UniMAP, Malaysia

E-mail: nasseersabri@yahoo.com

Abstract. Deployment of a successful wireless sensor network requires precise prediction models that provide a reliable communication links of wireless nodes. Prediction models fused with foliage models provide sensible parameters of wireless nodes separation distance, antenna height, and power transmission which affect the reliability and communication coverage of a network. This paper review the line of sight and the two ray propagation models combined with the most known foliage models that cover the propagation of wireless communications in vegetative environments, using IEEE 802.15.4 standard. Simulation of models is presented and the impacts of the communication parameters, environment and vegetation have been reported.

1. Introduction
Pervasive networks, represented by wireless sensor actor network, emerge the promises of automation the environment with sensors-actors wireless nodes which yielding a new era of environment automation applications [1] [2]. Currently, Wireless sensor network platform and applications are in an exponential growing. Initially, they were oriented for indoor applications such as, home automation and industrial control or for medical applications such as elderly monitoring [3]. Currently WSANs are adopted in a wide range of applications including telemedicine, home and building automation, surveillance systems and agricultural, avoiding the expensive retrofit necessary in wired systems. WSN nodes are highly constrained in terms of physical size, power consumption of CPU and transceiver, memory size and bandwidth. For remote nodes, the power consumption is considered a crucial parameter and have to care precisely where energy efficiency is paramount and batteries may have to last for years. Indeed, challenging physical environment like heat, dust, moisture, rain and interference [4].

WSN applications are growing exponentially and one of the most promising applications is the precision agriculture. Precision agriculture is one of the promising domains where wireless sensor networks could be exploited, for example, by observing the micro-climate within a field so that, ultimately, plant-specific farming can be realized. Agricultural application relies on the use of new era of WSAN to endorse monitoring and controlling management of a field based on site conditions [4]. WSNs offer a great flexibility when deploying new systems and when updating existing systems [5]. Since vegetation areas are cover a large portion of the Earth’s surface, the propagation of radio waves in a forest has long been of researcher’s interest. Radio waves propagating in vegetation usually experience much higher path loss than in environments without vegetation. Therefore, well known of the propagation mechanisms through a forest is critical for communication and sensing in such
environments. However, WSN nodes are spatial distribution in the field and must consider all the parameters that may have effects the wireless channel communication. Currently, the most promising of WSN technology in agricultural field is ZigBee [6-8]. This protocol has been widely adopted by WSN developer’s community; it relies on the IEEE 802.15.4 standard [9]. ZigBee technology is a low rate, low cost, low power consumption wireless node protocol aiming to remote and automation application systems.

ZigBee is expected to provide low power and cost connectivity for nodes that need long operation of battery of several years with low data rate. The IEEE-ZigBee are expected to transmit over 10-75 meters based on the RF power output consumption for specific application and the environment, and operates in the unlicensed RF worldwide 2.4 GHz with 250 Kbps data rate. To determine the behaviour of electromagnetic waves , a precise model of propagation must be adopted, however models normally used in wireless communication might not be precise describe the wireless sensor network. WSN node are spatially located, usually, near the earth surface thus may induce absence of main ray between sender-receiver nodes which is known of no line of sight (NLOS) status occur, although WSN nodes have spatially short distance distribution. Therefore, WSN propagation waves may face obstacle like trees, fence, building and dense foliage.

2. Radio Wave Propagation

The wireless radio channel faces a severe challenge as a medium for reliable high speed communication. It is susceptible to interference, noise, and other channel impediments which may change over time in unpredictable ways due to nodes-user movement. Path loss is caused by dissipation of the power radiated by the transmitter as well as effects of the propagation channel. Generally, path loss models propose that path loss is same for a given distance between sources of transmit and receive. Shadowing is caused by obstacles between the transmitter and receiver which will attenuate the signal power through reflection, diffraction, absorption, and scattering. For high level of attenuation, the signal will be blocked. Variation due to path loss occurs over very large distances (100-1000 meters), whereas variation due to shadowing occurs over distances proportional to the length of the obstructing object (10-100 meters in outdoor environments and less in indoor environments) [10, 11]. Such an environmental parameters not foreseen by developers and neither considered by theoretical models, and not accounted by simulators [11, 12] are affecting the wireless communication link. This is especially true for an arable farming environment in which foliage, growing crops, and ever changing weather conditions have an unknown effect on the exact propagation of the radio waves. The wireless channel is modelled based on several key parameters. These parameters vary significantly with the environment, rural versus urban, or flat versus mountainous. Different kinds of fading can be categorized in three types [13] [14]:

- **Distance Dependence** of path loss (measured in dB) is approximated by \( L(d) = L_0 + 10n \times \log(d/d_0) \), where \( n \) is the path loss exponent, which varies with terrain and environment, and \( L_0 \) is the path loss at an arbitrary reference distance \( d_0 \).

- **Large-scale Shadowing** causes variations over larger areas, and is caused by terrain, building, and foliage obstructions; the large-scale fading due to various obstacles is commonly accepted to follow a log-normal distribution [15]). This means that its attenuation \( x \) measured in dB is normally distributed \( N(m, \sigma) \), with mean \( m \) and standard deviation \( \sigma \). The probability density function of \( x \) is given by the usual Gaussian formula.

- **Small-scale fading** causes great variation within a half wavelength. It is caused by multipath and moving scatters. Resulting fades are usually approximated by Rayleigh, Rican, or similar fading statistics – measurements also show good fit to Nakagami-m and Weibull distributions.

Radio systems rely on diversity, equalizing, channel coding, and interleaving schemes to mitigate its impact. There are different propagation characteristic of different spectrum bands which require different prediction models. Some propagation models are well suited for computer simulation in
presence of detailed terrain and building data; others aim at providing simpler general path loss estimates [14, 15]. Wireless sensor network of mobile nodes are burdened with particular propagation complications, making reliable wireless communication more difficult than fixed communication between and carefully positioned wireless nodes. The antenna height at a mobile terminal is usually very small, typically less than a few meters. Hence, there is very little clearness, so obstacles and reflecting surfaces in the vicinity of the antenna have a substantial influence on the characteristics of the propagation path. Moreover, the propagation characteristics change from place to place and, if the terminal moves, from time to time.

Path loss models define the attenuation of a signal as a function of the propagation distance between a transmit and a receive antennas and other parameters. Some models include many details of the terrain profile to estimate the path loss, while others just consider the signal frequency and the separation distance. Antenna heights are other critical parameters [13].

2.1. Free Space Propagation

The free space propagation model assumes the influence of the earth surface to be entirely absent. This model assumes that the transmitter and receiver antennas to be located in an otherwise empty environment. Neither absorbing obstacles nor reflecting surfaces are considered [13][14]. The radiated energy is spread over the surface of a sphere of radius d, so as the propagation distance increases, the power received decreases proportional to $d^{-2}$. The received power is

$$P_{\text{dB}} = P - 20\log_{10}(d / d_o)$$

Hence, the free space propagation model assumes ideal propagation condition that there is only one clear line-of-sight path between the transmitter and receiver. A physical argument of conservation of energy leads to the Friis’ power transmission formula in free space. A transmitted power source $P_t$ radiates spherically, with an antenna gain $G_t$; the power density $W$ at distance $d$ from a transmitter with power $P_t$ and antenna gain $G_t$ is

$$W = P_t G_t / 4\pi d^2$$

The portion of that power impinging an effective area $A_e$, hence at a distance $d$, the power is $P_r = P_t G_t A_e / (4\pi d^2)$. The effective area of an antenna is related to antenna gain by $A_e = \lambda^2 G_t / 4\pi$, which is used for the receiving antenna, and thus yields [13, 14]:

$$P_r = P_t G_t G_r (\lambda / 4\pi d)^2$$

$P_t$, $G_t$ and $P_r$, $G_r$ are the transmitted and received power and gain respectively, $\lambda$ is the wavelength of the signal, and $d$ is the separation distance. The product $G_t P_t$ is called the effectively radiated power (ERP) of the transmitter. The path loss reflects how much power is dissipated between transceiver and receiver antennas (without counting any antenna gain). Path loss is often expressed as a function of frequency ($f$), distance ($d$), and a scaling constant that contains all other factors of the formula. Equation 3 shows a free-space dependence in $1/d^2$, and is sometimes loss is expressed in decibels (dB):

$$L(\text{dB}) = 10 \times \log(P_t/P_r)$$

For instance, when $f_o = 1\text{MHz}$, and $d_o = 1\text{km}$, the loss expressed as:

$$L(\text{dB}) = 32.44 + 20\log_{10}(f / f_o) + 20\log_{10}(d / d_o)$$

The free space model basically represents the communication range as a circle around the transmitter. If a receiver is within the circle, it receives all packets. Otherwise, it loses all packets.

2.2. Two-ray ground reflection model

Ray tracing is a method that uses a geometric approach, and examines what paths the wireless radio signal takes from transmitter to receiver as if each path was a ray of light (possibly reflecting off surfaces). Ray-tracing predictions are good when detailed information of the area is available. But the
predicted results may not be applicable to other locations, thus making these models site-specific. The well-known two-ray model uses the basic FSP model with a function that combine the reflected signal which shows a fading effects on received signal. The fact that for most wireless propagation cases, two paths exist from transmitter to receiver: a direct path and a reflected off the ground. That model alone shows some important variations of the received signal with distance [13]. The two-ray ground reflection model considers both the direct path and a ground reflection path. This model gives more accurate prediction at a long distance than the FSM as shown [13, 14]. The received power at distance $d$ is predicted by

$$P_r = \frac{G_T G_R \lambda^2}{(4\pi D)^2} \left[2\sin \left(\frac{2\pi h_t h_r}{\lambda d}\right)\right]^2$$  \hspace{1cm} (5)$$

$$d_{th} = \frac{4\pi h_t h_r}{\lambda}$$  \hspace{1cm} (6)$$

Where $h_t$ and $h_r$ are the heights of the transmitter and receiver antennas respectively, $d_{th}$ is defined as a turnover point where the argument of the sine tends to be equal to $\pi/4$. For example, carrier frequencies of 2400 MHz, a base station height of 4 meter and a fixed wireless node of antenna height of 1 meter, the turnover distance is about 128 meters as shown in figure 1. Hence for wireless sensor network nodes, distances less than than turnover distance are more relevant. The direct path (using the first term only of equation (5)) leads to the simple on-slope free-space model; the complete expression leads to the two-ray model, which shows interesting characteristics:

- The presence of a second ray causes great variations: signals can add up or nearly cancel each other, causing deep fades over small distances.
- In close proximity, the overall envelope of power decay varies in $1/d^2$.
- After a certain cutoff distance (approximately $4h_t h_r/\lambda$) the model approaches power decay in $1/d^4$.

The full path loss expression shows an interference pattern of the line-of-sight and the ground-reflected wave for relatively short ranges, and a rapid decay of the signal power beyond the turnover distance. It can be shown that for distances substantially greater than turnover point $d$, $d >> (h_t h_r)^{0.5}$, the reflection coefficient tends to -1, path loss tends to the fourth power distance law (7) and in dB, we have (8):

$$P_r = \frac{P G_T G_R h_t^2 h_r^2}{d^4}$$  \hspace{1cm} (7)$$

$$P_r(dBm) = P_r(dBm) + 10\log_{10}(GT) + 20\log_{10}(h_t h_r) - 40\log_{10}(d)$$  \hspace{1cm} (8)$$

The above equation shows a faster power loss than equation (3) as distance increases. However, the two-ray model does not give a good result for a short distance due to the oscillation caused by the constructive and destructive combination of the two rays. Instead, the free space model is still used when $d$ is small. Therefore, a turnover distance $d_{th}$ is calculated in this model. When $d>d_{th}$, equation (3) is used. When $d<d_{th}$, equation (7) is used. At the cross-over distance, equation (3) and equation (7) give the same result. The power fall off with distance in the two-ray model can be approximated by averaging out its local maxima and minima. This results in a piecewise linear model with three segments, which is also shown in figure 2, is slightly offset from the actual power falloff curve for illustration purposes. In the first segment, the power fall off is constant and proportional to $1/(d^2 + h_t^2)$, for distances between $h_t$ and $d_{th}$ power falls off at -20 dB/decade, and at distances greater than $d_{th}$ power falls off at -40 dB/decade.
Figure 1. Two ray propagation where transmit antenna is at 4m and receive antenna is at 1m

2.3. Shadowing
In real environment, the received power at certain distance is a random variable due to multipath propagation effects, which is also known as fading effects while the FSP model and the TRP model predict the received power as a deterministic function of distance. They both represent the communication range as an ideal circle. In fact, the above two models predicts the mean received power at distance \( d \). A more general and widely-used model is called the shadowing model [13]. The shadowing model is based on two parts. The first part is known as path loss model, which is predicts the mean received power at distance \( d \), denoted by \( P_r(d) \).

Figure 2. Received Power versus Distance for Two-Ray Model

It uses a close-in distance \( d_o \) as a reference. \( P_r(d) \) is computed relative to \( P_r(d_o) \) as follows;

\[
\frac{P_r(d)}{P_r(d_o)} = \left( \frac{d}{d_o} \right)^\alpha
\]  

(9)

\( \alpha \) is called the path loss exponent, and is usually empirically determined by field measurement. From equation (3) we know that \( \alpha = 2 \) for free space propagation. \( P_r(d_o) \) can be computed from (3). The path loss in dB is;

\[
\left[ \frac{P_r(d)}{P_r(d_o)} \right]_{dB} = -10\alpha \log_{10} \left( \frac{d}{d_o} \right) + \sigma_{dB}
\]  

(10)
The second part of the shadowing model reflects the variation of the received power at certain distance. It is a log-normal random variable, that is, it is of Gaussian distribution if measured in dB. The overall shadowing model is represented by:

\[ P_r(d)_{in} = P_r(d_o) - 10\alpha \log_{10}\left(\frac{d}{d_o}\right) + \sigma_{dB} \]  \hspace{1cm} (11)

Where \( \sigma_{dB} \) is a Gaussian random variable with zero mean and standard deviation. It is called the shadowing deviation, and is also obtained by measurement. Equation 11 is also known as a log-normal shadowing model. The shadowing model extends the ideal circle model to a richer statistic model: nodes can only probabilistically communicate when near the edge of the communication range.

3. Foliage Loss

Research on propagation loss due to foliage has focused mainly on forests \[16, 17\]. There are several models to evaluate the path loss of a propagation path due to the presence of foliage. Most of these models are based on working frequency \( f \) and foliage depth \( d_f \) which is represented by the expression of equation (12) \[18\]. The excess path loss \( L_{veg} \) due to foliage is based on the frequency of the travelled signal \( f \) and the depth of the foliage along this distance, while \( A, b, c \) are constant empirically determined.

\[ L_{veg} = A \times f^b \times d^c \]  \hspace{1cm} (12)

The Weissberger MED (Modified Exponential Decay) model \[18\]; Equation 13 expresses the excess path loss due to foliage, in dB,

\[ L(dB) = \begin{cases} 0.588 \times f^{0.284} \times d_f^{1.33} & \text{if } d_f < 14 \times f^{0.284} \\ 0.45 \times f^{0.25} & \text{if } d_f < 14 \end{cases} \]  \hspace{1cm} (13)

where \( f \) is in GHz and \( d_f \) is in meter; There are other propagation models that are in the form of (4), Based on same parameters and units as the MED model are: Early ITU model, equation (14), Fitted ITU-R model, equation (15);[19-22].

\[ L(dB) = 0.2 f^{0.3} d_f^{0.6} \]  \hspace{1cm} (14)

\[ L(dB) = 0.39 f^{0.39} d_f^{0.25} \]  \hspace{1cm} (15)

For single vegetation obstruction model \[22\], the foliage influence in dB is expressed as a function of distance \( d \) in meter and the specific attenuation for short vegetative paths in dB/m in equation (16),

\[ SV = d^\gamma \]  \hspace{1cm} (16)

4. WSN Wave Propagation Based on Agricultural Applications

WSN applications require RF or microwave propagation from point to point very near the earth’s surface and in the presence of various impairments propagation losses over terrain, foliage, and/or buildings may be attributed to various phenomena, including diffraction, reflection, absorption, or scattering. As a result the received signal power is attenuated and hence the communication range will
be limited. When WSN deployed, almost the distance between the wireless nodes is small, so the earth curvature could be neglected [21]. The wireless nodes antenna height within agricultural is less compared to the transmission range of WSN hardware. In this case the TR model [13] can be applied. Equation 7, which reads in logarithmic form, for isotropic antennas where the propagation loss follows the inverse fourth law with distance. The received power falls by $12dB$ when the distance is doubled. Therefore, for short range near ground vegetation environment, the total loss of propagation is modelled by fusion of the foliage imposed effect and the reflections effect of the radio wave bounce off the ground. Hence The total accumulated path loss ($TAP\_Loss$) is expressed as the summation of the path loss ($FSP\_Loss/\varphi TRP\_Loss$) due to wave spreading and the foliage excess loss ($Veg\_Loss$) in the propagation path, equation (17);

$$TAP\_Loss = FSP\_Loss + Veg\_Loss$$

(17)

Figure 3 shows that the loss follow $1/d^2$ for first 100m for various antenna heights 4, 3, 2 with receiver antenna of 1m height. Thus, WSN applications which uses like these heights for nodes antennas will suffer the FSP model attenuation which is approximately equal to the average of maxim-minim fluctuation of the TR model for fist hundred meters. Figure 4 shows comparisons of the Weissberger and ITU models, for foliage depths of 2 and 4m. Note that the frequency scale is in GHz for each plot, but the frequency used in the model is MHz for the ITU model as specified. The plots indicate a moderate variation between the models, particularly as frequency increases. The amount of foliage loss is monotonically increasing with foliage depth and frequency as expected based on equations (13) and (14), where the MED model yields of less losses. Therefore, modelling the path losses based on foliage models yield different losses, hence those models can be used only when their results are validate with an experimental work to find the right model that reflect the losses of the application.
5. CONCLUSIONS
Path loss prediction model is very important step in designing a WSN, the precise prediction models are needed to determine the parameters that affects the radio waves and could lead to efficient and reliable coverage of a specified service area. The effect of the foliage in the propagation of WSN waves can be predicted using propagation models. Thus, an appropriate propagation model based on the environment condition and the WSN application should be used.
This paper review FSP model and the TRP model, and introduce the fusion of propagation models with foliage models to predict the path loss within vegetation area. Using of TRP model depend on dc, so either reception power decay proportional to inverse of $d^2$ for distances less than $d_{th}$, or proportional to inverse of $d^4$. The separation distance of WSN nodes are almost around tens of meters and antenna height range from few centimetres above ground to few meters based on the application requirement. Thus, TRP model is used for path loss prediction for application need like different height of antennas and near ground propagation environment, therefore, it is highly occurs that a line of sight combined with a reflected components received at the receiver antenna. Different propagation models have different results and this yield to prior careful study of path modelling for WSN applications.
WSN requires a proper spatial node distribution strategy to achieve high communication reliability between sensor nodes. Therefore, a precise path loss propagation model should be adopted to find antenna heights and path loss within the limits of network connectivity and coverage range.

References
[1] R. Morais, M. A. Fernandes, S. G. Matos, C. Serodio, P. Ferreira, and M. Reis, “A zigbee multi-powered wireless acquisition device for remote sensing applications in precision viticulture,” Computers and Electronics in Agriculture, vol. 62, no. 2, pp. 94 – 106, 2008.
[2] D. Estrin, D. Culler, K. Pister, and G. Sukhatme, “Connecting the physical world with pervasive networks,” Pervasive Computing, January- March, 2002.
[3] N.K. Suryadevara, A. Gaddam, R.K. Rayudu, S.C. Mukhopadhyay 2012. “Wireless SensorsNetwork Based Safe Home to Care Elderly People: Behaviour Detection”. Procedia Engineering Volume 25, 2011, Pages 96–99.
[4] Naseer Sabri, S.A. Aljunid M.F. Malek, A.M. Badlishah, M.S. Salim, R. kamaruddin. “Wireless Sensor Actor Networks Application for Agricultural Environment,” IEEE Symposium on Wireless Technology and Applications(ISWTA), 2011.
[5] C. Serodio, J. B. Cunha, R. Morais, C. Couto, and J. Monteiro, “A networked platform for agricultural management systems,” Computers and Electronics in Agriculture, vol. 31, no. 1, pp. 75–90, March 2001.
[6] ZigBee Alliance, ZigBee Specification, v1.0, 2006A.
[7] Camilli, C. E. Cugnasca, A. M. Saraiva, A. R. Hirakawa, and P. L. Correa, “From wireless sensors to field mapping: Anatomy of an application for precision agriculture,” Computers and Electronics in Agriculture, vol. 58, no. 1, pp. 25–36, 2007.

[8] N. Wang, N. Zhang, and M. Wang, “Wireless sensors in agriculture and food industry–recent development and future perspective,” Computers and Electronics in Agriculture, vol. 50, no. 1, pp. 1–14, January 2006.

[9] IEEE standard 802.15.4 – Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate. Wireless Personal Area Networks (LR-WPANs), IEEE, 2003.

[10] T. Sarkar, J. Zhong, K. Kyungjung, A. Medouri, and M. Salazar-Palma, “A survey of various propagation models for mobile communication,” IEEE Antennas and Propagation Magazine, vol. 45, no. 2, pp. 51–82, June 2003.

[11] T. J. Andersen, T. Rappaport, and S. Yoshida, “Propagation Measurements and Models for Wireless Communications Channels,” IEEE Communications Magazine, vol. 33, no. 1, pp. 42–49, January 1995.

[12] B. Sklar, Digital Communications Fundamentals and Applications, 2nd ed., Prentice-Hall, 2000

[13] River, NJ, 2001, pp. 286–290. P. Mestre, C. Serodio, R. Morais, J. Azevedo, and P. Melo-Pinto, “Vegetation growth detection using wireless sensor networks,” Proceedings of The World Congress on Engineering 2010, WCE 2010 Lecture Notes in Engineering and Computer Science, vol. I, 2010, pp. 802–807.

[14] T. Rappaport, Wireless Communications: Principles and Practice, 2nd ed., Upper Saddle River, NJ: Prentice Hall, 2002.

[15] Goldsmith, Wireless Communications, New York: Cambridge University Press, 2005.

[16] H. L. Bertoni, Radio Propagation for Modern Wireless Systems, (Upper Saddle River, NJ: Prentice-Hall Inc., 2000).

[17] Y. S. Meng, Y. H. Lee, and B. C. Ng, “Path loss modeling for near-ground vhf radio-wave propagation through forests with tree-canopy reflection effect,” Progress In Electromagnetics Research M, vol. 12, pp. 131–141, 2010.

[18] K. Sarabandi and I. Koh, “Effect of canopy-air interface roughness on hf-vhf wave propagation in forest,” IEEE Transactions on Antennas and Propagation, Vol. 50, No. 2, February, 2002.

[19] M. A. Weissberger, “An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Trees,” Electromagnetic Compatibility Analysis Center, Annapolis MD, Final report, 1982.

[20] CCIR, “Influences of terrain irregularities and vegetation on tropospheric propagation,” tech. rep., CCIR Report, July 1986.

[21] J. D. Parsons, The Mobile Radio Propagation Channel, 2nd ed., Wiley, West Sussex, 2000

[22] ITU-R Recommendations, Attenuation in vegetation, ITU-R P.833-3