Analysis of Factors Influencing Communication and energy Consumption in Wireless Sensor Networks

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Abstract – The analysis and experiments presented in this paper are connected with propagation of signals between sensor nodes located in open area. The main purpose is to show some factors that affect the accuracy and reliability of the received signal strength (RSS) measurement as well as the determination of The Path Losses (PL), The Path Loss constant (n) and The Standard deviation (σ). The main factors considered here are: position and antenna orientation of sensor nodes and the distance between them.

Keywords – model; network; outdoor; propagation; sensor; wireless.

1. Introduction

This article presents various cases of transmitting data between wireless sensor nodes located in open areas. In the experiments performed, the received signal strength (RSS) is measured. Then, through calculations, the following values were found:

- 1) PL - Path Loss.
- 2) n - Path Loss constant.
- 3) σ - Standard deviation.
- 4) Pr(d) - Received Power as a function of distance.

DOI: 10.18421/TEM92-04

<https://doi.org/10.18421/TEM92-04>

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Received: 20 February 2020.

Revised: 09 April 2020.

Accepted: 17 April 2020.

Published: 27 May 2020.

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- 5) $\Pr[\Pr(d) > \gamma]$ - The probability of received power of the signal to be greater than the set level (threshold) γ [dBm].
- 6) $U(\gamma)$ - Percentage prediction of whether the received power inside the area with a given radius (d) will be greater than a given threshold γ [dBm].

For more accurate representation of PL, the Path-loss Shadowing Model - **PLSM** (also known as Log-normal Shadowing Model) is used [11], [12], [13].

This propagation model is very useful because it determines the transmitter coverage area and propagation losses [9], [10]. We can accurately define the communication radius between nodes at a given specific power and transmission frequency. Furthermore, not only we can calculate the transmission power required, but also the battery life of the sensor nodes (SN).

Using this model, we can determine relatively accurately the energy capacity of a Wireless Sensor Network (WSN) even before it is built.

2. Model

The *Path-loss Shadowing Model* described by the formula is used:

$$PL[dBm] = PL(d_0) + 10 \lg(d/d_0) + X_\sigma \quad (1)$$

This is an empirical model that analytically approximates the measurement results [5], [6], [7].

The strength of the received signal RSS as a function of distance (d) can be represented by [8]:

$$RSS[dBm] = P_t - PL(d) \quad (2)$$

and

$$RSS[dBm] = P_t - PL(d_0) - 10 \lg(d/d_0) - X_\sigma \quad (3)$$

where d is the transmit-receive distance (T-R), d_0 is the reference distance, P_t is the transmission power

in [dBm], PL is the Path losses in [dB], n is the Path Loss constant. X_σ is a random variable with Gaussian distribution with zero mean and standard deviation σ [dB] [2]. X_σ has an approximate value of 8 to 10 dB (9 dB is taken into account for calculations here) and can be found by the formula [3]:

$$X_\sigma(RSS) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(RSS-\mu)^2}{2\sigma^2}\right) \quad (4)$$

where μ is the average value of RSS (assumed to be zero here).

Finding n and σ :

The least squares method: MMSE (*minimum mean square error*) is used to find the Path Loss constant (n) and standard deviation (σ).

I take into account the fact that the reference distance for the propagation of signals is $d_0 = 1$ m and that the losses for this distance in the particular case PL(d_0) are known.

The sum of the quadratic error to be minimized is [4]:

$$S(n) = \sum_{k=0}^N (p_k - p'_k)^2 \quad (5)$$

where by p_k , I denote the received RSS power calculated by the equation,

$$p'_k = RSS_k = RSS_k(d_0) - 10\lg(d_k/d_0) \quad (6)$$

and with p_k , the power received from the measurements. Here $k = 1, 2, \dots, N$, and N is the total number of measurements taken.

The *minimum* requirement is expressed as follows:

$$\frac{dS}{dn} = 0 \quad (7)$$

whence we mathematically determine the Path Loss constant (n).

The standard deviation (σ) [dB] is given by the formula:

$$\sigma[\text{dB}] = \sqrt{S(n)/N} \quad (8)$$

It is found that as the number of measurements N increases, the parameter (σ) decreases.

Calculation of the received power at a certain distance:

To calculate the received power P_r ($P_r = \text{RSS}$) at a specified distance (d) from the transmitter, having found (n) and (σ), we can use the equation [8]:

$$P_r(d) = \text{RSS}(d) = \text{RSS}(d_0) - 10\lg(d/d_0) + X_\sigma \quad (9)$$

When we know the transmission power P_t , we can also use equation (3) to calculate the received power $P_r(d)$.

Calculation of the probability that the received signal P_r is greater than the set threshold γ :

The following equation:

$$\Pr[P_r(d) > \gamma] = Q\left(\frac{\gamma - P_r(d)}{\sigma}\right) \quad (10)$$

is obtained for this probability [4], in which

$$Q(z) = 0.5[1 + \text{erf}(z/\sqrt{2})] \quad (11)$$

Percentage prediction for an area with a given radius d , that determines whether the received power inside the area will be greater than a given threshold γ :

The probability that the signal level obtained is greater than γ [dBm] is represented according to the following equation [4]:

$$U(\gamma) = 0.5 \{1 + \exp(1/b^2)[1 - \text{erf}(1/b)]\} \quad (12)$$

where parameter (b) is defined by equation

$$b = (10\lg e)/(\sigma\sqrt{2}) \quad (13)$$

3. Experimental Setup

The experiments are made in the area of the University of Patra – Greece. The sensor nodes (Tmote Sky and TelosB), as well as the whole measurement equipment, are supplied by the Laboratory – APEL (Applied Electronics Laboratory) at the Electrical and Computer Engineering Department.

Figure 1. Experimental setup

The scheme of the experimental setup is shown in Figure 1. The sensor nodes are mounted on two two-meter tripods. The first tripod (from right to left in the figure) is fitted with a transmitter (T), located at a height of 1.1 m from the ground.

4. Experiments and Results

Every 150 msec it transmits a packet of information to the receiving node (R) located on the second tripod at a height of 2 m from the ground. Each packet contains 21 bytes, and for each measurement 100 packets are transmitted from T to R [1].

Figure 2. Open-air parking

RSS measurements were made in an open-air parking area (Figure 2) in line-of-sight (LoS) transmission between nodes. The main objective of the experiment is to calculate (n) and (σ) by the obtained results, and thus to make an analysis of the influence of environmental factors on the propagation of signals at different locations (horizontal and vertical) of the nodes in relation to each other in the particular environment.

Received information from (R) is transmitted to the Base Station (BS), which is connected via USB to a laptop where it is processed and RSSI (Receive Signal Strength Indicator) is extracted from it. Then, through additional calculations, the received RSS power is obtained using the known formula from the

Manual:

$$\text{RSS[dBm]} = \text{RSSI_VAL} + \text{RSSI_OFFSET} \quad (14)$$

In (14), $RSSI_OFFSET$ is the empirically found value of RSSI from the experiment.

For this purpose, a special software program running on the TinyOS operating system was used, as shown in Fig.3.

According to the CC2420 specification, $RSSI_VAL$ is -45 dBm. Therefore, if we extract the RSSI Number -20 (which we already mentioned is $RSSI_OFFSET$) from the program register, then the strength of the received signal according to (14) will be $RSS = -20 + (-45) = -65$ dBm.

```

Terminal - tiny2@ShimmerLive: ~/tinyos-main/apps/Bphd/javaF
File Edit View Terminal Go Help
Setting up for TinyOS 2.x
tiny2@ShimmerLive:~$ ls
Desktop Documents Downloads Public tinyos-2.x-contrib tinyos-main
tiny2@ShimmerLive:~$ cd tinyos-main/
tiny2@ShimmerLive:~/tinyos-main$ cd apps/
tiny2@ShimmerLive:~/tinyos-main/apps$ cd Bphd/
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd$ ls
Bc javaF RssiDemoMessages.h Rx Tx
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd$ cd javaF
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd/javaF$ motelist
Reference Device Description
-----
MFV694SM /dev/ttyUSB0 FTDI MTM-CMS000MSP
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd/javaF$ ls
Koridor1 Laboratories Offices RssiDemo.class RssiMsg.class
Koridor1 Zemya Makefile Proba RssiDemo.java RssiMsg.java
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd/javaF$ rm results.txt
rm: cannot remove 'results.txt': No such file or directory
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd/javaF$ rm results.txt
tiny2@ShimmerLive:~/tinyos-main/apps/Bphd/javaF$ java RssiDemo -comm serial@dev
/ttyUSB0:115200
serial@dev/ttyUSB0:115200: resynchronising

Terminal - tiny2@ShimmerLive: ~/tinyos-main/apps/Bphd/javaF
File Edit View Terminal Go Help
UNTER = 88
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 89
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 90
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 91
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 92
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 93
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 94
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 95
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 96
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 97
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 98
Message received from node 1: ID = 30: POWER = 0: CHANNEL = 26: RSSI = -25: PCO
UNTER = 99

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Figure 3. Program for finding $RSSI_OFFSET$

Measurements were made at two positions of the sensor nodes in relation to each other:

- Horizontally (H) - with antennas pointing up and power batteries - down;
- vertically (V) - with antennas facing each other.

The layout of the experimental set-up is the same as it is shown in Fig. 1, but in one of the measurements the nodes are horizontally and in the other - vertically oriented to each other (Fig.4). The transmission frequency is 2,480 GHz and the transmission power is $P_t = 0$ dBm. The information packets are transmitted sequentially from T to R and from there to BS connected via USB to the Laptop.

Figure 4. a) Horizontal (H) and b) Vertical (V) positioning of sensor nodes

The calculations of RSS and PL in a) and b) case follow the same sequence as described in details

above. The results from calculations are presented in Table 1, shown graphically in Figure 5.

Table 1. Results from the experiment, $P_t = 0$ dBm; $f = 2.480$ GHz; $d = 1 - 50$ m

d (m)	RSSI(H) (dBm)	RSSI(V) (dBm)	RSS(H) (dBm)	RSS(V) (dBm)	PL(H) (dB)	PL(V) (dB)
1	5	15	-40	-30	40	30
2	-13	5	-58	-40	58	40
3	-15	-17	-60	-62	60	62
4	-15	-8	-60	-53	60	53
5	-8	-16	-53	-61	53	61
6	-15	-27	-60	-72	60	72
7	-25	-14	-70	-59	70	59
8	-23	-17	-68	-62	68	62
9	-24	-27	-69	-72	69	72
10	-23	-15	-68	-60	68	60
11	-16	-16	-61	-61	61	61
12	-24	-43	-69	-88	69	88
13	-26	-19	-71	-64	71	64
14	-35	-14	-80	-59	80	59
15	-23	-15	-68	-60	68	60
16	-18	-16	-63	-61	63	61
17	-34	-23	-79	-68	79	68
18	-28	-39	-73	-84	73	84
19	-29	-29	-74	-74	74	74
20	-38	-23	-83	-68	83	68
22	-27	-21	-72	-66	72	66
24	-24	-20	-69	-65	69	65
26	-17	-20	-62	-65	62	65
28	-22	-23	-67	-68	67	68
30	-26	-26	-71	-71	71	71
32	-25	-28	-70	-73	70	73
34	-44	-34	-89	-79	89	79
36	-36	-44	-81	-89	81	89
38	-38	-38	-83	-83	83	83
40	-41	-36	-86	-81	86	81
42	-43	-35	-88	-80	88	80
44	-35	-33	-80	-78	80	78
46	-39	-31	-84	-76	84	76
48	-34	-30	-79	-75	79	75
50	-35	-30	-80	-75	80	75

a) Horizontal position of SN - $n_H = 2.2053$; $\sigma_H = 6.011$

b) Vertical position of SN - $n_V = 3.1111$; $\sigma_V = 8.3022$

Figure 5. Graphics of RSS and PL with Horizontal and Vertical orientation of SN

Having found the Path Loss constant (n) and the standard deviation (σ) for the two cases in a) horizontal and b) vertical positioning, I can now calculate a few more things:

- the received power $Pr(d)$ at a specified distance $d = 32$ m;
- the probability that the received signal $Pr[Pr(d) > \gamma]$ is greater than the set threshold $\gamma = -77$ [dBm];
- the percentage prediction $U(\gamma)$ for an area with a given radius d , that determines whether the

received power inside the area will be higher than the set threshold $\gamma = -77$ [dBm].

a) Horizontal node positioning.

a1) Calculation of the received power $Pr(d)$.

From (9) for $d=32$ m it follows:

$$P_r(d=32m) = -40 \text{ dBm} - 10(2.2053)\lg(32/1) + 9 \text{ dB} = -64.2 \text{ dBm}.$$

a2) Calculation of the probability that the received signal $Pr[P_r(d) > \gamma]$ is greater than the set threshold γ [dBm].

I set the threshold to be $\gamma = -77$ dBm. Then from (10) and (11) it follows:

$$Pr[P_r(d) > \gamma] = Q(-2.13) = 0.0166 = 1.66 \%$$

a3) Percentage prediction for an area with a given radius d , that determines whether the received power inside the area will be greater than the given threshold γ [dBm].

The probability is represented by equation (12) and (13) and after a substitution the result is:

$$U(-77 \text{ dBm}) = 33.5\%$$

b) Vertical node positioning.

b1) Calculation of the received power $Pr(d)$.

From (9) for $d=32$ m it follows:

$$P_r(d=32\text{m}) = -30 \text{ dBm} - 10(3.1111)\lg(32/1) + 9 \text{ dB} = -67.82 \text{ dBm}$$

b2) Calculation of the probability that the received signal $Pr[P_r(d) > \gamma]$ is greater than the threshold γ [dBm].

The threshold is again $\gamma = -77$ dBm and from (10) and (11) it follows:

$$Pr[P_r(d) > \gamma] = Q(-1.106) = 0.11 = 11 \%$$

b3) Percentage prediction for an area with a given radius d , that determines whether the received power inside the area will be higher than the given threshold γ [dBm].

The probability is represented by equation (12) and (13) and after a substitution the result is:

$$U(-77 \text{ dBm}) = 39.33\%.$$

5. Conclusion

The experiments presented in this article aim to show some factors that affect the accuracy and reliability of the received signal strength (RSS) measurements as well as the determination of losses (PL), Path Loss constant (n) and standard deviation (σ). The factors considered are: distance between transmitter and receiver (d) and antenna position and

orientation of sensor nodes. In the experiments performed, the transmission frequency (f), transmission power P_t and the environment did not change.

To determine the losses, one statistical distribution model was used: *Path-Loss Shadowing Model* (PLSM). It is also known in the literature as *Log-normal Shadowing Model* (LNSM). This model is simple and realistic, because it takes into account the losses of shading. By determining the losses at the reference point PL (d_0), as well as the Path Loss constant (n) and the standard deviation (σ), the PLSM calculated the received power at a given distance.

The experiments were made with sensor nodes - Tmote Sky and TelosB in open spaces (car parking) in the area of the University of Patras, Greece.

The results and conclusions obtained from these experiments are summarized as follows:

RSS measurements were made in direct line of sight (LoS) between sensor nodes at two positions:

a) horizontally and b) vertically oriented.

From the results obtained, it was found that, when two different positions of the nodes relative to the ground (horizontal and vertical) are used with the same parameters set in both cases (environment, height of SN, frequency, distance and transmission power), there is a difference in the values obtained for RSS, PL and (n). It can be seen that in vertical positioning the losses are generally smaller (Table 1). This may be mainly due to the different antenna pattern in the different planes. This should be taken into account when constructing a wireless sensor network. Another reason for this difference can be found in the fact that the scattering environment is less inhomogeneous in the vertical plane than in the horizontal plane.

Furthermore, the following additional calculations were made in this experiment: Calculation of the received power $Pr(d)$ at a given distance $d=32$ m; Calculation of the probability $Pr[P_r(d) > \gamma]$ that the received signal is greater than a threshold $\gamma=-77$ dBm; the percentage prediction $U(\gamma)$ for an area with a given radius d , showing whether the received power inside that area will be higher than the set threshold $\gamma = -77$ [dBm]. It can be seen that when we have the vertical positioning of the sensor nodes, $Pr[P_r(d) > \gamma]$ and $U(\gamma)$ are bigger. This, in turn, makes communication in this case better and more reliable.

Based on the results obtained, the parameters of a WSN can be calculated and its efficiency can be predicted.

A multi-hop model can also be applied further on to reduce losses in communication between sensor nodes and thus to optimize the wireless sensor network.

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