

Link Layer Models for Wireless Sensor Networks

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IMPORTANT Please read this document before using the software tools.

This document is a tutorial version of [1], its main purpose is to provide enough information and tools to generate link layer models for wireless sensor networks (WSN), namely the packet reception rate (PRR) as a function of distance. It is recommended that you read [1] to gain a deeper understanding of the wireless link behavior in low power wireless devices.

The document is divided in three sections. Section I provides a basic understanding of the channel and radio models used to generate the link layer abstraction (PRR vs distance). Section II provides a systematic way to obtain link layer models for different environments and radio characteristics, it also provides instructions to use the software tools. Finally, section III enumerates the limitations of the model generator.

I. THE CHANNEL AND RADIO MODELS

The particular behavior of the wireless link is the result of placing specific devices, for example MICA2 motes, in an specific environment, like the aisle of a building. Hence, first let us define models for both, radio and channel, to subsequently study their interaction.

A. The Wireless Channel

When an electromagnetic signal propagates, it may be diffracted, reflected and scattered. These effects have two important consequences on the signal strength. First, the signal strength decays exponentially with respect to distance. Second, for a given distance d , the signal strength is random and log-normally distributed about the mean distance-dependent value.

One of the most common radio propagation models is the log-normal shadowing path loss model [2]¹:

$$PL(d) = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

¹The model is valid only for the transmission frequency and environment where the data was gathered.

Where d is the transmitter-receiver distance, n the path loss exponent (rate at which signal decays), X_σ a zero-mean Gaussian (in dB) with standard deviation σ (multi-path effects), d_0 a reference distance and $PL(d_0)$ the power decay for this distance. Usually, n and σ are obtained through curve fitting of empirical data.

The received signal strength (P_r) at a distance d is the output power of the transmitter (P_t) minus $PL(d)$, i.e. $P_r = P_t - PL(d)$ (all powers in dB).

B. The Radio

Usually, the radio does not send '0s' and '1s' directly, but it *encodes* them into bauds. This process is called encoding, and one baud can be less, more or equal to 1 bit. After encoding, the radio uses a *modulation* mechanism to send these bauds over the wireless channel. The radio have several options; it can modulate the amplitude, frequency or phase of the carrier frequency.

Both, the encoding and modulation used, play an important role on the link behavior of WSN. To facilitate the explanation of the radio model, this subsection assumes that 1 bit = 1 baud (NRZ encoding), and that the radio modulates the frequency of the carrier (non-coherent frequency shift keying - NCFSK).

In the presence of additive white gaussian noise (AWGN) the probability of bit error P_e of the receiver is given by:

$$P_e = \frac{1}{2} \exp^{-\frac{\gamma}{2}} \quad (2)$$

Where γ is the signal to noise ratio (SNR). P_e depends on the modulation used, the above equation correspond to NCFSK.

A frame is received correctly if all its bits are received correctly, hence, for a frame² of length f the probability of successfully receiving a packet is:

$$p = (1 - P_e)^{8f} \quad (3)$$

²A frame consists of: preamble, network payload (packet) and CRC

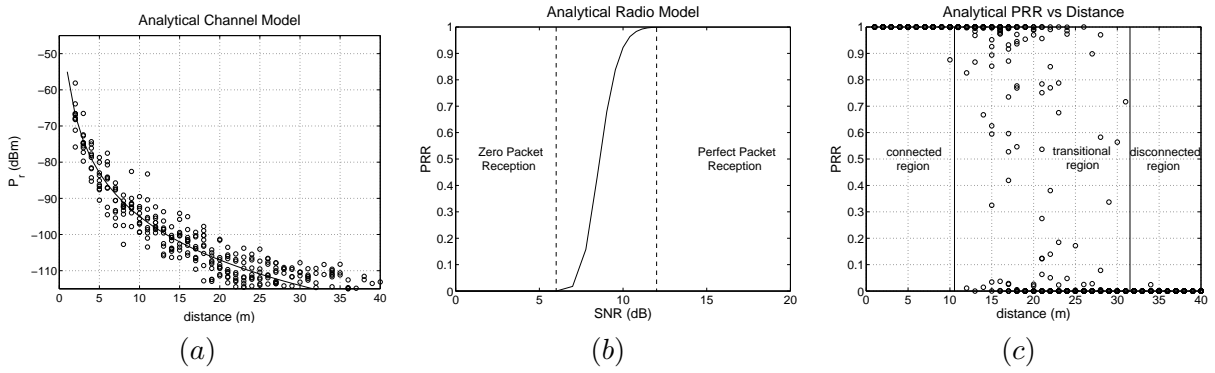


Fig. 1. (a) Channel Model, (b) Radio Model, (c) Link Layer Model

Finally, by inserting eq. 2 in eq. 3, the PRR p is defined as:

$$p = \left(1 - \frac{1}{2} \exp^{-\frac{\gamma}{2}}\right)^{8f} \quad (4)$$

C. The Noise Floor

Another important element that determines the link behavior is the noise floor. The temperature of the environment influences the thermal noise generated by the radio components (noise figure)³. When the receiver and the antenna have the same ambient temperature the noise floor is given by [2]:

$$P_n = (F + 1)kT_0B \quad (5)$$

Where F is the noise figure, k the Boltzmann's constant, T_0 the ambient temperature and B the equivalent bandwidth. Please refer to [1] for a detailed analysis of the noise floor.

D. Combining Radio and Channel Behavior

Given a transmitting power P_t , the SNR at a distance d is (all powers in dB):

$$\gamma(d) = P_t - PL(d) - P_n \quad (6)$$

Henceforth, the PRR at a distance d for the encoding and modulation assumed in this section is:

$$p(d) = \left(1 - \frac{1}{2} \exp^{-\frac{\gamma(d)}{2}}\right)^{8f} \quad (7)$$

Please refer to [1] for equations to determine the width of the transitional region.

³Interfering signals can further influence the noise floor. In [4], the authors present a model for interference that can be used to complement ours.

E. Asymmetric Links

Link asymmetry is the result of hardware variance in the noise floor and output power. Our model simulates hardware variance through a joint gaussian process:

$$\begin{pmatrix} T \\ R \end{pmatrix} \sim \mathcal{N} \left(\begin{pmatrix} P_t \\ P_n \end{pmatrix}, \begin{pmatrix} S_T & S_{TR} \\ S_{RT} & S_R \end{pmatrix} \right) \quad (8)$$

Where the covariance matrix S shows the variance of the output power, noise floor and the correlation between them.

II. METHODOLOGY

Table I shows the steps required to generate the link layer models.

First, obtain the output power (T_i) and noise floor (R_i) for all nodes ($i = 1, \dots, N$). Nominal values for MICA2 motes are $-20 \text{ dBm} < P_t < 5 \text{ dBm}$, $P_n = -105 \text{ dBm}$, these (average) values are modified by the covariance matrix, which for MICA2 motes is:

$$S = \begin{pmatrix} 3.7 & -3.3 \\ -3.3 & 6.0 \end{pmatrix}$$

Second, obtain the channel characteristics, namely, path loss exponent, shadowing standard deviation, d_0 and $PL(d_0)$. These parameters can be obtained by performing your own measurements or by using values from other studies ([3] provides a comprehensive list).

Third, obtain the SNR $\gamma(d)$ for a given transmitter-receiver distance.

Fourth, based on the modulation used by the radio (NCFSK for MICA2) select the respective expression for the bit error rate and insert $\gamma(d)$ (not in dB, i.e. convert $\gamma_{dB}(d)$ obtained in the previous step to $10^{\frac{\gamma_{dB}(d)}{10}}$).

Finally, based on the encoding scheme select the respective equation for the packet reception rate. The model assumes that the preamble ℓ is not encoded, and hence is the same for all encoding schemes. Other radio designs may lead to slightly different expressions.

A. Software Tool

The software tool follows the steps described above with some security checks added, and it is provided in two languages, Java and MATLAB.

The various channel and radio parameters can be modified inside *inputFile.m*. The tool allows the creation of different topologies: grid, uniform, random and user-defined.

for **JAVA**: download the *LinkLayerModelJAVA.zip* file which contains:

- LinkLayerModel.java
- inputFile.m
- topologyFile.m

First compile the code by typing:

```
$ javac LinkLayerModel.java
```

Then, run the following command:

```
$ java LinkLayerModel inputFile.m outputFile
```

Where *outputFile* is any name you want to give. *outputFile* will show the placement of the nodes, as well as a matrix with the PRR for all the links in the network.

for **MATLAB**: download the *LinkLayerModelMATLAB.zip* which contains:

- LinkLayerModel.m
- inputFile.m
- topologyFile.m
- prr.m
- Q.m

LinkLayerModel.m does not require input arguments, except when the user defines the topology. When no user-defined topology is given the command is:

```
> [topo, prrM] = LinkLayerModel;
```

topo is a Nx2 matrix with the coordinates of the nodes (first column X coordinates, second column Y coordinates.). *prrM* is a NxN matrix with the link quality (between 0 and 1).

When a topology is given, the command is:

```
> [topo, prrM] = LinkLayerModel(userTopo);
```

prr.m is a function that can be used to calculate the PRR for a given link. This function is useful in case the user wants to obtain the PRR for specific links inside his/her own script and not as a separate topology. For *prr.m*, the channel and radio parameters have to be given as arguments.

Notice that while *LinkLayerModel.m* includes asymmetry, *prr.m* requires the output power and noise floor as input arguments and hence asymmetry should be already considered in the input parameters.

Other works can be used to complement our model. For instance, contention models can be inserted from [4], and correlations due to direction of propagation from [5].

Temporal properties are also an important part of the channel behavior and other studies [6] can be built on top of our work. However, for several low dynamic scenarios targeted for WSN, such as those in remote locations, our work can be an important modeling tool.

Finally, it is important to remark that the log-normal shadowing model is not valid for distances less than d_0 . Hence, do not expect to see nodes closer than d_0 . The tool have security checks to provide topologies that satisfy this requirement. In order to attain these internode distances, densities higher than $\frac{0.5 \text{ motes}}{m^2}$ are not allowed (and Error will be printed).

REFERENCES

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- [5] G. Zhou, T. He, S. Krishnamurthy, and J. Stankovic. "Impact of radio irregularity on wireless sensor networks". MobiSys '04.
- [6] A. Cerpa, J. L. Wong, M. Potkonjak and D. Estrin, "Temporal Properties of Low Power Wireless Links: Modeling and Implications on Multi-Hop Routing", ACM Mobihoc, Urbana-Champaign, IL, May 2005.

III. LIMITATIONS OF THE TOOL

Our study does not consider interference effects and it is focused on static and low-dynamic environments.

STEP 0 : Radio	Obtain output power and noise floor for all nodes according to equation 8
T, R	For MICA2: $-20 \text{ dBm} < P_t < 5 \text{ dBm}$, $P_n = -105 \text{ dBm}$ Cholesky decomposition can be used to generate multivariate random variables.
STEP 1 : Channel	Obtain channel parameters
$PL(d_0), n, \sigma$	Can be obtained through own empirical measurements, or from some published results [3]
STEP 2 : SNR	Obtain SNR as a function of distance d
$\Upsilon_{dB}(d)$	$T - PL(d_0) - 10n \log_{10}(\frac{d}{d_0}) - N(0, \sigma) - R$
STEP 3 : Modulation	Select P_e according to the modulation used, insert $\gamma(d)$ not in dB, i.e. $10^{\frac{\Upsilon_{dB}(d)}{10}}$ Convert from $\frac{E_b}{N_0}$ to $RSSI$ by inserting the appropriate bit data rate R and noise bandwidth B_N
ASK	noncoherent: $\frac{1}{2} [\exp^{-\frac{\gamma(d)}{2} \frac{B_N}{R}} + Q(\sqrt{\gamma(d) \frac{B_N}{R}})]$ coherent: $Q(\sqrt{\frac{\gamma(d)}{2} \frac{B_N}{R}})$
FSK	noncoherent: $\frac{1}{2} \exp^{-\frac{\gamma(d)}{2} \frac{B_N}{R}}$ coherent: $Q(\sqrt{\gamma(d) \frac{B_N}{R}})$
PSK	binary: $Q(\sqrt{2\gamma(d) \frac{B_N}{R}})$ differential: $\frac{1}{2} \exp^{-\gamma(d) \frac{B_N}{R}}$
STEP 4 : Encoding	Select packet reception rate according to the encoding scheme, frame and preamble lengths
NRZ	$(1 - P_e)^{8\ell} (1 - P_e)^{8(f-\ell)}$
4B5B	$(1 - P_e)^{8\ell} (1 - P_e)^{8(f-\ell)1.25}$
Manchester	$(1 - P_e)^{8\ell} (1 - P_e)^{8(f-\ell)2.0}$
SECDED	$(1 - P_e)^{8\ell} ((1 - P_e)^8 + 8P_e(1 - P_e)^7)^{(f-\ell)3.0}$

TABLE I
THEORETICAL MODELS FOR THE LINK LAYER