Link Layer Models for Wireless Sensor Networks

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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 also provides a basic understanding of simple concepts in wireless communication (used in the model) for people who does not feel comfortable with the physical layer. 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 the link layer model 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. Please make sure you read this document completely before using the software tools.

IMPORTANT if you do not understand something, specially the first section, just move on, hopefully it will be clear at the end :).

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, the radio and the 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.

Due to the unique characteristics of each environment, most radio propagation models use a combination of analytical and empirical methods. One of the most common radio propagation models is the log-normal shadowing path loss model [2][1]:

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + X_\sigma \qquad (1)$$

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

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

Once the link layer has '0s' and '1s' ready to send. The radio has to decide whether to send "raw" bits or *encode* them in some fashion. This process is called encoding, and this is the point where the bits convert to bauds. One baud can be less, more or equal to 1 bit.

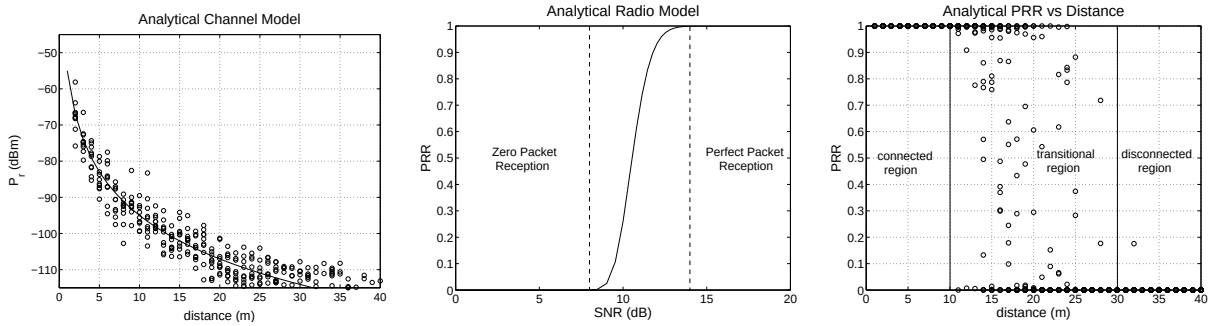
Once the radio has decided on how to encode the bits (now bauds), it faces another important decision: how is it going to send these bauds over the wireless channel?. The radio have several options; it can modify the amplitude, frequency or phase of the carrier frequency, this process is called modulation. Both, the encoding and modulation used, play a major 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 modifies 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 is given by:

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

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

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



(a) (b) (c)

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

A frame is received correctly if all its bits are received correctly, hence, for a frame[2] of length f the probability of successfully receiving a packet is:

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

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

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

C. The Noise Floor

Another important element that determines the link behavior is the noise floor, which depends on both, the radio and the environment. The temperature of the environment influences the thermal noise generated by the radio components (noise figure). The environment can further influence the noise floor due to interfering signals. When the receiver and the antenna have the same ambient temperature the noise floor is given by [2]:

$$P_n = (F + 1)kT_0B \tag{5}$$

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. Putting all Together

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

$$\gamma(d) = P_t - PL(d) - P_n \tag{6}$$

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

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

Please refer to [1] if you are interested in the expressions for the width of the transitional region (a.k.a the gray area).

II. Methodology

Table I shows the steps required to generate the link layer models. The next paragraphs explain these steps.

First, the model requires the channel characteristics, namely, path loss exponent, shadowing standard deviation, d_0 and $PL(d_0)$. You can obtain these parameters by performing your own experiments, or by using values from other studies. [3] provides a comprehensive list of channel parameters for different environments.

Second, you need to obtain the SNR, $\gamma(d)$, for a given transmitter-receiver distance. In order to obtain the SNR, in addition to the channel parameters, we require the output power of the nodes and the noise floor. Notice that the values on STEP 2 should be in dB (or dBm). Common values for MICA2 motes are $-20\ dBm < P_t < 5\ dBm$, $P_n = -105\ dBm$.

Third, based on the modulation used by the radio (NCFSK for MICA2) select the respective expression for the bit error probability 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 basically follows the steps described above with some security checks added. The model generator is provided in two languages, Java and MATLAB,

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

STEP 1 :	Obtain channel parameters.
$PL(d_0), n, \sigma$	own empirical measurements, or from published results [3]
STEP 2 :	Obtain SNR γ as a function of distance d.
$\gamma_{dB}(d)$	$P_t - PL(d_0) - 10nlog_{10}(\frac{d}{d_0}) - N(0,\sigma) - P_n$
STEP 3 :	Obtain P_e according to modulation used.
Non-Coherent ASK	$\frac{1}{2}[\exp^{-\frac{\gamma(d)}{2}} + Q(\sqrt{\gamma(d)}\,)]$
Coherent ASK	$Q(\sqrt{\frac{\gamma(d)}{2}})$
Non-Coherent FSK	$\frac{1}{2}\exp^{-\frac{\gamma(d)}{2}}$
Coherent FSK	$Q(\sqrt{\gamma(d)}\,)$
BPSK	$Q(\sqrt{2\gamma(d)}\,)$
DPSK	$\frac{1}{2}\exp^{-\gamma(d)}$
STEP 4 :	Obtain PRR $p(d)$ according to the encoding scheme.
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

both provide the same results and the user can choose the version he/she feels more comfortable with.

The tool allows the creation of different topologies: grid, uniform, random and the input from a user file. All these options are explained in the sample input file provided (*inputFile.m*). This file also contains the required parameters for the channel and radio models.

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

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

First compile the code by typing:

```
$ javac LinkLayerModel.java
```

Two warnings may appear, do not worry about them. 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

The MATLAB script does not require inline inputs, just type:

```
> LinkLayerModel
```

inputFile.m and the *topologyFile.m* are the same for both, JAVA and MATLAB. However, for MATLAB the input-file and topology-file names should be *inputFile.m* and *topologyFile.m* respectively; and they have to be in the same directory as *LinkLayerModel.m*. Also, the line "TOPOLOGY_FILE = ..." in *inputFile.m* should be commented out for using it with MATLAB. The topology and packet reception rate (prr) matrices will be saved in LinkModel.mat.

prr.m is a function that can be used to calculate the packet reception rate 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. The description of the input variables is given in *prr.m* itself.

III. LIMITATIONS OF THE TOOL

This tool have some limitations. First, the models does not capture interference. However, the channel model can be used to consider P_r signals for non-intended receivers as noise. Despite this fix, a more detailed study may be needed to accurately quantify the impact of interference on the wireless link.

Second, the model does not consider the time domain, i.e. the PRRs obtained are for a snapshot of time. Nevertheless, if the environment is static (i.e. static nodes, and no dynamic objects around them), time variations are mainly due to the fluctuations in the noise floor. Hence, time-variant links could be modelled by a gaussian distribution of the noise floor, and use these samples as the noise floor for each received packet, instead of the deterministic value assumed in these tools[3].

[3]For more challenging dynamic environments, richer time-varying fading models are required.

Third, the way we represent asymmetric links is by running to different instances of the channel model (equation 1) for the RSSI values (one for each direction). Research has shown that the main causes of asymmetry are calibration errors in the transmitting power and sensitivity of the radios, hence, the asymmetric characteristics of the network are not modelled accurately.

We are currently working on models to fix these three limitations and they should be available soon.

Finally, the inter-node distance can not be less than d_0 (default value is 1 meter), this is not a limitation of the tool, but rather an inherent limitation of the channel model. The channel model requires a close-in reference distance loss $PL(d_0)$, and is not valid for distances less than d_0. The tools have security checks to provide topologies that satisfy this requirement. Hence, do not expect to see nodes closer than d_0 in the *outputfile*. In order to attain these internode distances, densities higher than $\frac{0.5\ motes}{m^2}$ are not allowed (and Error will be printed).

REFERENCES

[1] Marco Zuniga, Bhaskar Krishnamachari. "Analyzing the Transitional Region in Low Power Wireless Links". USC Tech Report 04-823.

[2] Theodore S. Rappapport. "Wireless Communications: Principles and Practice". Prentice Hall.

[3] K. Sohrabi, B. Manriquez, and G. Pottie, "Near Ground Wideband Channel Measurement", Vehicular Technology Conference IEEE, volume 1, pages 571-574, 1999.