Channel Modeling for WSN in Harsh Environments

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Abstract

In the past 10 years, the industry has strongly benefit from the wireless sensor network technology. However, the harsh environment in which this networks are deployed, makes urgent to develop empirical and computational models that predict the network performance in such hostile environment. One particular harsh environment is the minning industry, in which the physical characteristics of the tunnel and rooms make this modeling even harder. A review of those models is presented, together with suggestions of possible continuation of the presented works
Keywords: WSN, Channel modeling, minning industry, Zigbee, IEEE 802.15.4

1 Introduction

In todays competitive industrial sector, the manufacturers invest significant amount of money to ensure that the plants function with full capacity and efficiently with zero downtime and without unanticipated output quality. Thus, Selection of the right technology for the required application is challenging for the industrial environment. Furthermore, interferences to the mission-critical data can result in costly disasters in terms of money, manpower, time and even lives of employees or public[1], as it was showed in [2]. For example, the productivity and efficiency of current industrial facilities can be greatly improved by using wireless sensor network technology for remote control and automation as well as for efficient data collection[3]. In wired networks, each sensor node requires a separate twisted shielded pair wire connection. That becomes expensive if the cabling across sensor nodes and the controllers are long and configuration management is difficult. Wireless sensor network (WSN) is relatively very cost efficient. Moreover, its self-configure, self-organizing characteristics make the wireless sensor networks robust and ideal for hazardous plant and high-assets protection applications[1].

As several authors have reported[1, 4, 5], the industrial environment is not the best environment for setting up a WSN. The effect of noise due to the broad operating temperatures, heavy machinery, ignition systems, vibration among other usual industrial activities is high. Also, the interference due to the use of the 2.4GHz Industrial, scientific and medical (ISM) unlicensed frequency by other technologies like Wifi, Bluetooth, wireless USB, microwaves, cordless phones and other sources is an undesired effect that must be also taken into account. If not, the aforementioned propagation effects can significantly degrade the performance of WSNs in industrial settings. Knowledge of the propagation channel is thus required to design and evaluate WSNs for industrial applications[3].

However, the knowledge of the propagation channel is not an easy task. It will highly depend on the characteristic of the industrial environment where the WSN is deployed. For example, the working infrastructure of an oil rig will be composed by several floors, where the ceil and the walls could be covered with steel piping, as showed in the experiment of Luo et al.[5]. On the other hand, a mining industry has a completly different setting, where the propagation characteristics of electromagnetic waves in underground mines are different from those in free space, because of the physical characteristics of the ore and the tunnel itself[6, 7, 8].

This paper will present the attempts on modeling the wireless channels for WSN in industrial environments, with an emphasis on the mining industry. Section I will present a brief explanation of a WSN, with emphasis on the protocol IEEE 802.15.4, the ZigBee Alliance and the characteristics of the physical layer. Section II will detail the characteristics that degradate the signal in a WSN link. In Section III the models that try to represent the industrial environment and the underground mining environment are presented, along with their results. Finally, Section IV present the discusion and conclusions.

2 Wireless Sensor Networks

Wireless sensor networks are systems that comprise large populations (hundreds or thousands) of wirelessly connected heterogeneous sensor nodes that are physically small, inexpensive and spatially distributed across a large field of interest. Moreover, they consume little power to allow prolong operation for years[1].

2.1 IEEE 802.15.4

IEEE 802.15.4 is a technical standard which defines the operation of low-rate wireless personal area networks (LR-WPANs). It specifies the two first layers of the OSI model, i.e., physical layer and media access control.

2.1.1 Physical Layer

IEEE 802.15.4 defines the physical layer with three possible operational frequencies, each one with different bitrate, channels and modulation scheme, which are presented in table 2.1.1. Additionally, the standard uses direct sequence spread spectrum (DSSS) modulation.[1]

2.1.2 MAC Layer

With regard to channel access, 802.15.4 uses carrier sense multiple access with collision avoidance (CSMA-CA). This multiplexing approach lets multiple users or nodes access the same channel at different times without interference. Most transmissions are short packets that occur infrequently for a very low duty cycle (≤ 1 %), minimizing power consumption.

2.2 ZigBee Alliance

The most widely deployed enhancement to the 802.15.4 standard is ZigBee, which is a standard of the ZigBee Alliance. The organization maintains, supports, and develops more sophisticated protocols for advanced applications. It uses layers 3 and 4 to define additional communications features. These enhancements include authentication with valid nodes, encryption for security, and a data routing and forwarding capability that enables mesh networking. The most popular use of ZigBee is wireless sensor networks using the mesh topology[2].

[1]http://www.electronicdesign.com/what-s-difference-between/what-s-difference-between-ieee-802154-and-zigbee-wireless

3 Noise, fading and interference in the Industrial Wireless Channel

3.1 Pathloss and fading

Cheffena defined very well the main sources of interference, noise and fading for an Industrial Wireless Channel (IWC). In particular, in his study[3, 4], he propose that one of the characteristics for an IWC is the heavy multipath propagation. Additionaly, he states that no clear relationship between path-loss exponent and frequency can be established for many industrial environment [3].

3.2 Noise

Usually, the noise in a wireless communication systems is characterized as AWG. However, in harsh factory environments, wireless systems are also affected by impulsive noise[1, 3, 9]. The figure 1 shows this behaviour. It can be seen that this kind of noise is a significant variable in the performance of a wireless system.

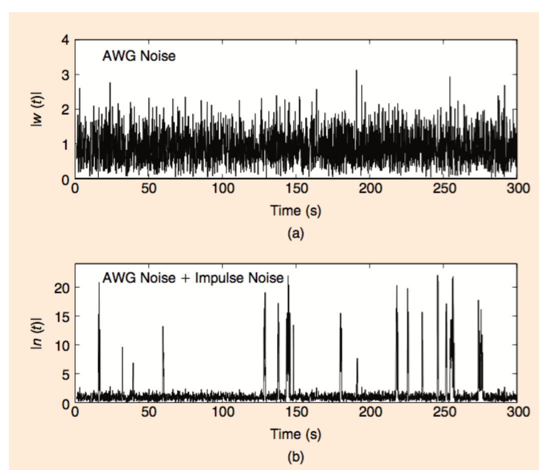

Figure 1: Simulated time series with AWGN (a) and AWGN + impulsive noise (b). Extracted from [3]

[2]http://www.zigbee.org/zigbee-for-developers/zigbee/

Characteristic	Europe	USA	Worldwide
Frequency Assignment	868 to 868.6 MHz	902 to 928 MHz	2.4 to 2.4835 GHz
Number of Channels	1	10	16
Channel Bandwidth	600 kHz	2 MHz	5 MHz
Data Rate	20 kbps	20 kbps	250 kbps
Modulation	BPSK	BPSK	O-QPSK

Table 1: Definitions of the PHY layer for IEEE 802.15.4

3.3 Interference

As it was stated before, several wireless technologies shares the 2.4GHz ISM band. In particular, for interference mitigation, IEEE 802.15.4 uses direct sequence spread spectrum (DSSS), dynamic channel selection (DCS), acknowledged transmission and retries (ATR) and clear channel assesment (CCA), to mitigate, avoid interference from other 2.4GHz radio products[3]. Additionally, the channels in this standar are designed so they do not collide with Wi-fi channels. In [1] are shown several narrow and broadband sources that may interfere the wireless channel.

3.4 Time Varying channel

The time-varying effects in industrial facilities are mainly caused by movements of workers, robots, trucks or other objects, that may cause time-varying channel conditions[3].

4 Models for Industrial Wireless Channel

It has been stated that there are several problems regarding the transmission of information from one node to another, in a WSN. In general, the authors agree that there are two methods for establish RF channels[5]: Simulation-based methods and measurement-based methods. Each method has its own advantages and drawbacks. While a simulation-based method could be cheaper, its computational cost is, sometimes, a burden that must be avoided. On the other hand, while measurement-based methods are easier to develop, their monetary cost could jeopardize a small research. The best choice is often, a mix between measure and models. However, the measurement results from one environment may not be applicable to other environment[3]. This big issue lead to several models that try, to the best of their efforts, to achieve certain degree of plausibility, while keeping the computational cost at some affordable quantity.

4.1 Industrial Environment

While most of the researchers try to gather data from the industrial environment and then adjust the data to some existing models[5, 8], others develop mathematical models that aim to be as broad and flexible as possible. Cheffena developed the **Composite Dynamic Wideband Channel Model**[4], in which he models the time varying channel with the combined effect of noise, interferences and multipath propagation. In particular, he considers the noise as a mix of AWGN and impulse noise; interference as the sum of the n-arriving signals, considering its power and phase; multipath propagation as result of reflection within an ellipse where the foci are the transmiting and receiving node; and finnaly, a time variation represented by a Doppler spectrum. The model is then described as followed:

$$\begin{aligned} h(t,\tau,\theta_{AoD},\theta_{AoA}) = \sum_{m=0}^{M-1} A_m(t)\delta[\tau-\tau_m(t)] \\ \delta[\theta_{AoD}-\theta_{AoD,m}(t)]\delta[\theta_{AoA}-\theta_{AoA,m}(t)] \\ \exp\left(j\left(\phi_m-\frac{2\pi d_m}{\lambda}\right)\right)+n(t)+J(t) \end{aligned} \tag{1}$$

4.2 Minning Environment

While in the previous sections the discussion has been about industrial indoor environments, another important environment is the minning sector. It is also a very harsh environment, not only for the humans, but also for the WSN. In fact, Grote[8], based on the previous works of Deryck[10], states that the working range of radio frequencies for free propagation is considered to lie between 500 and 2000 MHz. As it can be seen, way below the 2.4GHz ISM band that Zigbee uses. Additionaly, there is a key factor in undereground mines, as the tunnels can be treated as

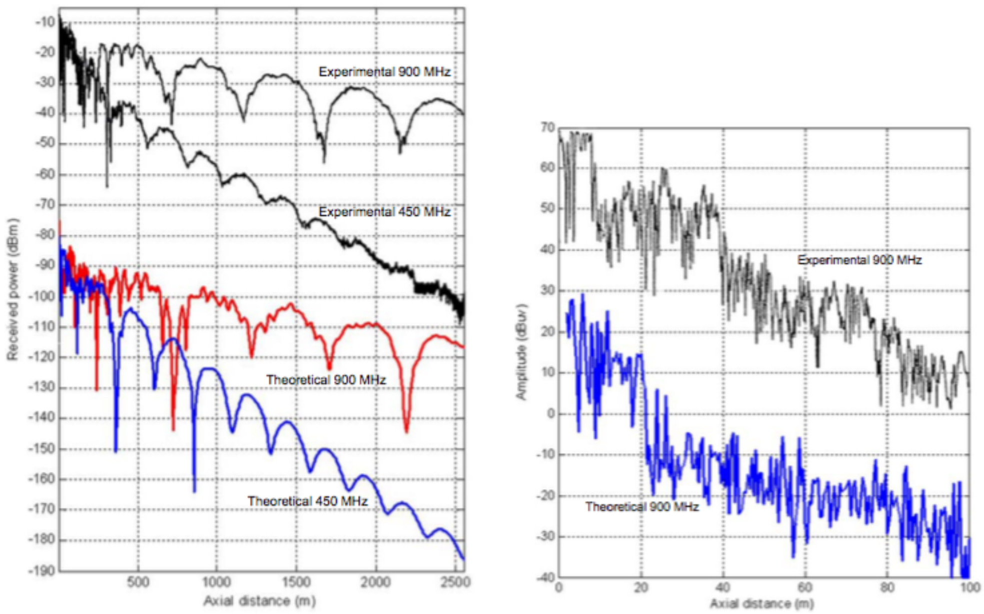

Figure 2: Left shows the simulations and experimental data for the multimode model in a Tunnel condition. The simulation curves are intentionally 75dB below, for comparision purposes. Right shows the simulation and experimental data in room-and-pilar condition. Simulated curves are 40dB below for comparision. Extracted from [7]

imperfect waveguides[6, 7, 8], since its walls are not perfect conductors, the electrical parameters are not well known and vary according to rock composition[8].

To overcome this drawback, again models and field test are usually conducted. Grote reported that, due to the wave guiding characteristics of the tunnel, the free-space equation, in Line of sight (LOS) conditions provides a good large scale propagation model for frequencies between 870 and 2450 MHz. However, there must be taken into account that his model only is valid for Mina El Teniente, in Chile, mainly because of the previous discusion about generalization in the results obtained from empirical data[3].

On the modeling side of the story, authors agree that undereground mines could be modeled with two kind of channel models: *Tunnel Channel Model and Room-and-pilar channel model*[6, 7]. For the Tunnel Channel model, currently there are three solutions:

- The Geometrical Optical Model, that can numerically predict the path loss and signal delay at any position, with a huge amount of data input for build the model.

- The Waveguide Model, that does not need detailed information of the tunnel and it is the only model that provides analytical solution,but it is not suitable to analyze the signal propagation near the transmiter, hence it cannot be used in high density networks, such as WSN.

- Full Wave Model, which uses finite-differente time-domain, providing very accurate results, using intensive computational resources.

With those elements, Sun & Akyildiz [7] developed a new model, the **multimode model** which takes into account the Tunnel Channel and Room-and-pilar channel mode. The results of their simulation is shown in the figure 2

On the other hand, Farjow et at. developed a model that divides the mine into three main segments, Line-Of-Sight (LOS), Partial-Line-Of-Sight(PLOS) and Non-Line-Of-Sight(NLOS). This model, called **Mine Segmening Wireless Channel Model**[6], in contrast with the Multimode model, does not uses Maxwell's equations for developing the model, but instead, uses a combination of statistical models that act together, to characterize a general area or areas within a mine.

5 Summary and Conclusions

In this article, a review for the modeling of industrial wireless channel for WSN was presented. The need for channel characterization was the key concept in all the reviewed literature, however, it is almost impossible to develop a general model for an industrial environment, so restrictions in data gathering and modeling is needed. In particular, some models seems to be quite useful for a broad kind of industries. That is the case of the Composite Dynamic Wideband Channel Model. Cheffena also propose that, for improve the performance, enhancing-techniques should be used, like adaptative coding and modulation, as well as MIMO techniques. This last point is quite interesting, because it proposes a new challenges in the design of WSN, because with more antennas, the nodes could use more energy endangering the batery's life of the node and, consecuently, the entire network.

While the mine models also show good performance, in particular the Multimode model, the link performance with that model is some work that could be done. Mostly because Sun & Akyildiz did the simulation for frequencies that are within the working range, as Grote reported. It could be very useful to adapt the multimode model, for a MIMO scheme, in 2.4GHz, and contrast the results. This work could lead to develop a testbed for the chilean minning industry, that may help develop new technology for improving productivity and for making a safer environment for the people that work there.

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