Real-Time Monitoring of Sand and Dust Storm Winds Using Wireless Sensor Technology

By
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Abstract

Title: Real-Time Monitoring of Sand and Dust Storm Winds Using Wireless Sensor Technology

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This dissertation proposes an empirical model for prediction of the radio path loss in Wireless Sensor Networks (WSNs). The model applies to WSNs that are deployed in environments with dust and sand storms. It is developed as a result of statistical analysis of the measured data collected during dust and sand storms. The measured data were obtained at 2.4GHz and for different levels of the storm severity. For the purpose of data collection a custom measurement system based on Xbee air interface was developed. The proposed model shows a very good agreement with the measured data. It is also demonstrated that the radio path loss correlates very well with the wind speed. Therefore, the wind may be considered as a principle source that determines the severity of the dust and sand storms from the path loss standpoint.
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<th>Description</th>
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<td>SDS</td>
<td>Sand and Dust Storm</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>WSNs</td>
<td>Wireless Sensor Network System</td>
</tr>
<tr>
<td>EiRP</td>
<td>Effective isotropic Radiated Power</td>
</tr>
<tr>
<td>ERP</td>
<td>Effective Radiated Power</td>
</tr>
<tr>
<td>EMW</td>
<td>Electro Magnetic Wave</td>
</tr>
<tr>
<td>FSPL</td>
<td>Free Space Path Loss</td>
</tr>
<tr>
<td>LDPL</td>
<td>Log-Distance Path Loss</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>PL</td>
<td>Path Loss PLE: Path Loss Exponent</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSL</td>
<td>Received Signal Level</td>
</tr>
<tr>
<td>RSLmin</td>
<td>Minimum Received Signal Level</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
</tbody>
</table>
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Dedication

To:

My advisor Dr. Kostanic
My father Mohammed
My mother Hajrah
My son Basil
My daughters Basayl and Lamar
My sisters and brothers
My brother Adeeb
My friend Marco Rossi
My friends Lyla Gwaher and Eiman

For their love and support.
Chapter 1: Introduction

The impacts of sand and dust storms in WSNs

Sand and dust storms (SDS) are natural disasters which are commonly seen in the Middle East, Northern Africa and Northern China. In those regions, SDS cause damages to the natural environment, national economy, and human health [39].

In Kingdom of Saudi Arabia, Riyadh city area, dust storms occurs regularly in the period from late February to late July. During this period, SDS will occurs at least two times a month. The wind speeds accompanying the dust storms may exceed 25 mph (40km) and cause weather conditions like the one seen in Figure 1. Due to strong winds, much of the sand is lifted in the air. It has been observed by several researchers [38, 15, 45] that a radio signal in the presence of the dust storms encounters an increase of the propagation path loss [25]. The effect is quite significant and it has a measurable impact on the operation of wireless systems in the area [45]. Therefore, in the process of wireless network planning, the potential of signal attenuation that is due to sand stores needs to be taken into account [33].
Figure 1: An example of environment of sand and dust storms in Riyadh city
To reduce the damages caused by the SDS, it is necessary to monitor their origin and development. To this end, wireless sensor networks (WSNs) can be deployed in the regions where SDS generally originate so that sensor nodes collaborate to monitor WSN and get the observations damages and send the data to administration center.

There are many unique challenges of the WSNs deployment in SDS environment like keeping the sensors alive and communication under increased propagation path loss. The increase of the path loss may render some portion of the network disconnected from the information sink. Therefore, the reliability of the network is impacted. The impact on the reliability needs to be taken into account during the network planning process.

This dissertation goal is to create an RF propagation model for WSNs in SDS environment. The wireless sensor network will be deployed in the sand and dust storm area. The software system is distributed across the WSN to provide real-time collection and transmission of data between wireless sensor nodes and a centralized server. The WSN nodes include: low transmission power, short-range communications and various sensors [7].

This thesis is organized in 6 chapters. Chapter 2 explain the problem statement and an overview of the RF propagation model and the background of wireless
sensor network to understand it in general. In addition, this section present the basic elements of WSN. Chapter 3 offer the simple summary of the published studies in WSNs with the basic propagating models which were used in WSN prior to this study. Additionally, Chapter 3 present the wireless technology and radio standards for WSNs which used for this research.

Chapter 4 describes the system used for data collection. It fully describes the hardware and software components of the system. For the work presented in this thesis this system was of a vital importance since it provided all the data for the study.

Chapter 5 provides modeling equations for a newly developed empirical model. The model provides the analytical means for the path loss prediction in the sand and dust storm environments.
**Wireless Sensor Network (WSN)**

Wireless Sensor Network is important technology in wireless communication which includes many sensor nodes connect with external antenna to communicate with each other in ad-hoc network to get the target for their application [4]. The wireless sensor network architecture is built up on hardware platform and an operating system to transmit and receive the data in physical deployment. This process made a bridge between the sensor nodes which have a low-power sources as batteries and solar cells. The structure of the WSN can be deploy indoor and outdoor as its target and environment conditions such as pressure, sound, temperture and wind [45]. The data passed through the sensor nodes to the basic station which could be laptop. Where the information is required for processing and analysis as illustrated in Figure 2 [26,45].

![Figure 2: Wireless Sensor Network (WSN) Architecture](image-url)
Any additional hardware is depend on the target of the application. These make the WSN be flexible and has low cost in any deployment. Any WSNs has five basic hardware components as shown in Figure 3 [34]:

1. Controller

2. Transceiver

3. Sensors: a microcontroller connect to the nodes wirelessly like wind sensors and humidity

4. Power source.

5. Storage to collect the data from the nodes like basic computer or external memory.
Figure 3: The basic hardware component of a sensor node

**Basics Wireless Sensor Technology**

Wireless Sensor technology consist of small miniature sensor devices to sense the data, process it and interface between it until it reach the concerned equipment. A numbers of these devices work together to form a network. These devices have limited consumptions power, memory and battery power, this being the reason they are need to be deployed in high number in a small area. The topology and positioning of the sensor network is carefully engineered. This network of sensor networks can be far away or close the actual phenomena, and their topology may change frequently. These sensing devices sense and collect the intended data and transmit it to the processing unit after regular interval of time [5, 51, 52]
**MAC Protocol for WSN**

Medium access protocol (MAC) is used to get the datalink layer access on the LAN. Since sensor networks are densely deployed in a place and the nodes have limited battery power, and topology of the sensor network is also likely to be changed rapidly. They need a MAC protocol which is contention free, consumes less energy. Scalable and adaptive to the situation. Beside this, the requirement for MAC protocol varies with the nature of application. IEEE802.11 is a family of the standard defined for wireless communication. Many MAC protocols have been proposed following the IEEE802.11 suitable for different applications e.g. Sensor-MAC (S-MAC), WiseMAC etc. Each one has its own pros and cons. So one should select the MAC protocol according to the needs of application [29, 22].

**Routing Protocol for WSN**

Routing protocol is basically to route the traffic within or outside the network from source to destination. Due to the many constraints in wireless sensor networks (WSN) like limited energy to work, get the location of other nodes, tight hardware resources and many other factor makes the problem of routing a challenging one. Many routing protocols have been proposed according to the requirements of the different applications [30]. They can be divided into seven categories Location-based routing protocols, Data-centric routing protocols, Hierarchical routing protocols, Mobility-based routing protocols, Multipath-based routing protocols, Heterogeneity-based routing protocols and QoS-based routing protocols [13].
**Localization of WSN**

Localization is to know the position of nodes in the network. It’s important to know the location of nodes to do the routing in network. Wireless sensor network (WSN) being dense network, it is not an energy efficient solution to install GPS on each and very node. Beside this energy efficiency problem, GPS do not work properly in indoor environment. This brings up the problem of localization in WSN. The other solutions for the localization are proximity based localization, angle bases, range based, distance based and the solution proposed under these categories are GPS, Bluetooth, AoA, ToA, and DV Hop respectively [23].

**WSN Applications**

Sensor nodes are of different type which vary in their sensing functionality. These nodes have the capability of sensing the existence of any targeted object in surroundings, the condition of lightening, the level of humidity in air or soil, the present temperature and the direction and movement of vehicles. These diverse functionalities make it appropriate for a number of applications. The wide range of application of wireless sensor network (WSN) includes disaster relief applications, military applications, biodiversity mapping, intelligent buildings, medicine and health care etc. [33].

**Wireless Sensor Node Architecture**

There are many proposed architectures for WSN. The most common follow the OSI model. This model needs five layer i.e. application layer, transport layer, network
layer, data link layer and physical layer as seen in Figure 4. Along with these layers, three cross layer planes are added. The three cross layer planes are power management, mobility management plane and task management system. Given the constraints of WSN, these layers are to manage the network and help it perform with great efficiency [21].

Figure 4: WSN protocol stack

**Topology of WSN**

Since wireless networks are very dense networks, the topology must be considered in design of network. The most common topologies are star, mesh and hybrid topology. Each topology has its own advantages and disadvantages for different applications. The table below illustrates the pros and cons of each topology [24].
Component of a WSN node
To perform all the sensing, processing and transmitting data from the environment, a sensor node consists of radio, battery, sensor interface, microcontroller and analog circuit.

Wireless Sensor Network Deployment
The deployment of the WSN depends upon the size of network and duration. It may encounter many problems. The common problems that can arise in the deployment of WSN are

Node Problem: The energy level of the node should be managed according to the duration of the specific application of WSN, as there is a risk of node’s death due to its low energy level [6].

### Table 1: The pro and cons of topology

<table>
<thead>
<tr>
<th>Topology</th>
<th>Power usage</th>
<th>Communication range</th>
<th>Requires time synchronization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>Low</td>
<td>Short</td>
<td>No</td>
</tr>
<tr>
<td>Tree</td>
<td>Low</td>
<td>Long</td>
<td>Yes</td>
</tr>
<tr>
<td>Mesh</td>
<td>High</td>
<td>Long</td>
<td>No</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Low(typically)</td>
<td>Long</td>
<td>(Depends on the configuration)</td>
</tr>
</tbody>
</table>


**Link Problem:** Link quality should be good enough to minimize the effect of interference and other factors affecting the link.

**Path Problem:** In many WSN topologies, there is a sink which collects the information and passes it on to other nodes. So the path to that sink must not be broken for continuous and better performance.

These are some of the issues that should be considered in the development of wireless sensor networks [53].
Chapter 2: Problem statement

Introduction

The propagation of EMW is severely affected by dust particles in terms of attenuation and de-polarization. There is a growing interest in the effect of dust particles on the propagation of microwaves. This is brought by the increasing number of terrestrial and satellite links in those regions that encounter dust and/or sand storms [48]. Computations of these effects require knowledge of electrical properties of the scattering particles and climate conditions of the studied region. Saudi Arabia has a large area and it is counted as a country having severe climate. Wireless communication networks are installed in areas where there are dust and sand storms that may affect the microwave signal propagation. When microwaves pass through a medium containing sand and dust particles, the signals get attenuated through absorption and scattering of energy out of beam by the sand and dust particles [15].

The purpose of this dissertation is to create an RF propagation model for WSNs in SDS environment. To acquire real time measurements using WSNs, the ground sensors deployed in the SDS area. The humidity, temperature, wind speed/direction, and RSSI will be measured by the sensors. The collected data will help to understand
the effects of SDS on RSSI and the path loss in WSNs and how large the propagation losses can be determine in sand storms.

**RF Propagation Model**

In wireless communication systems the signal waves travel between transmitter and receiver through a wireless channel which is the basic part of the wireless system. There are many factors affecting the propagation of the wireless signals in any environment. It can be interference, obstacles, refraction like buildings, trees, mountains, sand particles etc. [7]. All these constraints highly effect the radio wave transmitting data. The RF propagation model is defined as a mathematical formulation which is empirical type. Its purpose is to know the pattern of propagations in a given frequency, distance and some other conditions. Its help to find out how much the transmitted radio signal is going to be affected. This predict the path loss when a radio wave will pass through a link under specific constraints. For this reason engineers developed propagation models to predict the signal strength at the receiver. The RF propagation models are fundamental tool for designing a deploying any wireless communication system [20].
RF Propagation Model for WSN

The propagation of signal is degraded by the several factors, and this affects increases when it comes to wireless sensor networks. Reason behind this is WSN nodes generate low power radio due to their own energy constraints. And these low power radio are more affected by the environment factors. The result is the wireless paths in wireless sensor networks are most unpredictable. There are three mainly factor which affect the radio waves of wireless sensor networks.

**Surrounding environment:** The environment causes the multipath propagation of radio waves, it greatly affects and contributes in background noise which degrade the signal.

**Interference:** Due to the sources generating electromagnetic waves, and the concurrent signal transmission by different devices causes interference which effects the quality of radio wave.

**Hardware transceivers:** Since every equipment has some internal noise, the transceivers may affect the signal received due to their internal noise.

The low power signals of wireless sensor network are more vulnerable to the multipath distortion, internal noise of transceivers, and the interference of the environment. So the radio propagation model for WSN should cater for all these problems that affect the quality of signal.
Background Work in WSN

The conduct of the wireless sensor networks link is highly unpredictable since it changes within a small span of time. This lousy conduct of the link makes the estimation of link quality highly challenging for the researchers. But at the same time it is necessary for the designers to correctly estimate the link characterization in order to increase the performance of WSN. A lot of research has been done in this domain and many solutions came up in past for different scenarios. Most of the proposed solutions are empirical. But the problem is that the results of these studies are contradictory which can be due to the discrepancy an experimentation. However, this is an important direction which is getting a lot of attention in researcher community for link estimation is an important building block for all the other protocols of wireless sensor networks like MAC protocol, routing protocol etc.

Wireless System Elements

In WSN the signal travel in wireless mode. The elements required for its proper working are given below.

Gateway: It is an interface between the wireless sensor network and the application platform. It transmits the received information from the wireless sensor network to the application platform for the processing and manipulation [11].
Relay Node: It is just like router and considered a fully functioned device. Its work is basically to increase the network coverage area for WSN in case of any obstacle or device failure. It also provides back-up routes in case of congestion.

Leaf Node: leaf node is considered as reduced function device. Its works is to connect the wireless network to the wired network.

Sensor: Sensor is a small device which has its own sensing capabilities. It interacts with the surrounding environment or system in order to collect the different parameters the application needs for monitoring [12]

Effective radiated power (ERP)
ERP refers to Effective radiated power which is the output power of the transmitter (Pt), added in the gain of the transmit antenna (Gt) minus the losses in the transmitter (Lt) due to the connectors and path between transmitter and antenna [37]. The ERP present the signal power that leaves the transmitter antenna. The ERP always takes into account all the gains and losses on the transmit side. The term is mentioned as a standardized characterization outlined in IEEE for defining of RF power transmitted from a half-wave dipole antenna. So, from a mathematical perspective, this generates a virtual dipole antenna positioned in the direction where a receiver is stationed. Effective radiated power primarily takes into consideration the relative gain at the antenna rather than the absolute gain. So, in ERP, the antenna gain is considered as being absolute by default unless mentioned otherwise as relative. This antenna gain is consequently multiplied by the power received by an antenna to give the resultant
value of ERP. Additionally, losses in power take place prior to the antenna, for instance, as observed in case of a transmission line or the lack of efficiency in a generator and so not considered when calculating of ERP [56].

ERP is often expressed in $dBm$ and it given by

\[
ERP[dBm] = 10\log\left(\frac{P_t}{0.001}\right) + 10 \log (G_t) - 10 \log (L_t) \quad (1)
\]

**Received signal level in WSN**

The received signal level at the receiver referred as Received Signal Level (RSL) or Received Signal Strength Indicator (RSSI). Received signal level in wireless sensor network is the measurement of the power of signal at the receiver. These received signals loss their quality in different losses along the path, so its power and quality is measure accordingly. This information can be used to check if the level of signal is decreased than required value for the application, or to see if the channel is clear to send. The distance effect on the RSL the strength of the signal will be increased is the transmitter close to the receiver. While expressing the received signal strength, it is important to note that the fundamental difference between RSS and RSSI is that the former is the actual value whereas the latter is an indicator expressed as a relative value. Despite the fact that most RF values are often times negative and expressed in units of dBm, RSSI, being relative is always expressed as a positive value. These positive values for expressing of RSSI are derived via the scaling and conversion of negative values into positive ones. RSS, on the other hand, being an actual value
representing the strength of the signal recorded at the receiver and could be expressed in units of \(dBm, dB, \text{milliWatt} \text{ and } \text{Watt}\). In field experiments, the use of RSSI is vital as it tells researchers if they have sufficient amount of signal strength for getting a superior wireless connection. Per IEEE 802.11 standards, RSSI values can fall in the range of 0 to 255 and consequently, higher the value of RSSI, the better is the signal strength. The RSL is often expressed in \(dBm\), and it is given by:

\[
RSL[dBm] = 10 \log \left(\frac{Pr}{0.001}\right)
\]  

Equation (2)

\(RSL\) consist of receiver losses and gains. RSL could be presented without considering receiver gains and losses and computed at the receiver’s antenna point. These points are referred to as minimum receiver signal level \(RSL_{\text{min}}\) \([4]\) and do not include receiver antenna gains and losses. The following equation is used to denote \(RSL_{\text{min}}\) and it is given by

\[
RSL_{\text{min}}[dBm] = RSL[dBm] - Gr[dB] + Lr[dB]
\]

Equation (3)

\[
RSL_{\text{min}}[dBm] = RSL[dBm] - Gr[dB] + Lr[dB]
\]

Equation (4)
Where:

- $G_r$ refers to the receive antenna gain.
- $L_r$ refers to the receiver miscellaneous losses.

**Path Loss (PL)**
Path loss is degradation of the signal quality. The distance between nodes and the base station directly impacts the quality of the signal, as the distance increases the quality of signal decreases. Path loss occur due to the environment and its factors. The effect is different in different scenarios like urban, rural, vegetation or foliage, by different medium like dry, moist or air. The path loss in different scenarios in descending order is mentioned below.

- Urban area (large city)
- Urban area (medium and small city)
- Suburban area
- Open area

Path loss is computed and presented as a prediction, which is done primarily via the use of empirical, deterministic and stochastic models [57]. In case of empirical models, the prediction is based purely on the observations made in the field and the corresponding measurements. The deterministic models utilize the laws that control the electromagnetic propagation of waves to determine the strength of the signal.
received at a specific node. In contrast to empirical and deterministic models, the stochastic models are based on the environment presented as a sequence of randomly declared variables. In field studies, the path loss experienced by a wireless communication is reported in terms of path loss exponent with values ranging from 2 for free space to 4 for an environment experiencing comparatively greater losses. Buildings and similar indoor environments can have path loss values of greater than 4 and ranging up to 6, whereas relatively closed environments like a tunnel can record a lower path loss exponent of 2. It is commonly expressed in dB [59]. Propagation path loss can be defined as the difference between the ERP and $RSL_{min}$, which is given by

$$p_l[\text{dB}] = \text{ERP}[\text{dBm}] - RSL_{min}[\text{dBm}]$$

In free space propagation, however, the strength of the signal decreases only as a function of distance. To estimate signal strength in free space environment, Free Space Path Loss (FSPL) model is often used and is denoted as follows:

$$FSPL = \frac{(4\pi d)^2}{\lambda^2}$$
Where:

- $d$ is the distance between the transmitter and receiver in meters.
- $\lambda$ is the wavelength in meters

Since

$$\lambda = \frac{c}{f}$$

Where:

$c$: Light velocity in space [$3 \times 10^8 \text{ m/sec}$]
$f$: Operating frequency
Chapter 3: Literature review

Introduction

Environmental factors, primarily rain and dust arising from sandstorms have known to severely limit the propagation of electromagnetic waves. Especially in the Middle East, where sandstorms are a regular phenomenon, the particles of dust are known to cause attenuation and depolarization of the electromagnetic waves propagating in the sandy desert terrain [15]. This study, conducted in the southern part of Libya, focused on the weak signal strength propagated by the wireless communication systems installed in the region. The study was designed to determine if frequent dust and sandstorms arising in the region played a role in weak signal propagations. Samples were collected at nine different sites during various times of the year and analyzed by comparing them with the data recorded by global system for mobile communication. The sample collection took place from the roof tops of the buildings that were in the close vicinity of the communication towers and via the use of plastic cups situated in the towers at a height of 13 meters. The findings of the study reported that sand and dust particles did play a role in decreasing the signal strength in the region. Thus, the said issue about the signal attenuation caused by obstacles presented by dust particles has generated a growing interest in the study of such effects on the communication observed in the wireless sensor networks. The findings
of the research conducted by this dissertation will add to the very limited number of existing studies performed in the area.

The research presented in this dissertation is primarily based on the free space path loss model, two ray ground reflection model and log-distance path loss model, described in subsequent sections and adheres to the standards set per IEEE 802.15.4. A study indicated that a vast majority of research performed in the area of wireless sensor networks adopt either the free space path loss model or the two-ray path loss models. Both these models take a very simplistic approach and are known to produce extremely optimistic results in case of near ground propagation seen in many several WSN based outdoor applications [9]. In such environments the propagation of signal relies immensely on the type of terrain as well as any objects on that terrain acting as obstacles. Consequently, a study has reported significant differences in the received signal strength (RSS) deployed in various types of environments [2]. It is therefore vital that continuous characterization of signal propagation in other potential deployment environments remains an ongoing process. With that premise in background, this research details the RF measurements as well as path loss model for wireless sensor nodes deployed in a sandy desert terrain. The findings of this study should help in the design of precise and more accurate radio frequency propagation models that can ultimately aid in the successfully budgeting, planning and deploying a wireless sensor network.
Basic propagation model

A basic radio propagation model which is also referred to as the Radio Wave Propagation Model or the Radio Frequency Propagation Model is a mathematically calculated empirical representation of a radio wave in terms of its characters, mainly frequency and distance. A basic radio model is typically created with the goal of making an accurate prediction of the behaviors demonstrated by propagations under identical constraints. The propagation models are designed to formalize the technique used for propagation of radio waves from one point to another. These models thereby accurately predict the path loss observed along a link, or the total area covered by a transmitter, etc. Radio frequency propagation models play a vital role in the field of WSN and accurately computed RF propagation models can be aptly used for planning and deploying WSNs. Such models can help in increasing overall efficiency of a WSN by allowing for increased battery efficiency of the receiving and transmitting sensor nodes and providing an improved accuracy in terms of localization of applications based on the characteristics of the signal strength at the receiving node. These benefits consequently help in proper budgeting of a project while also acting as efficient cost-saving measures. Majority of the RF propagation models implemented in the modern day WSNs were actually created for the purpose of making accurate predictions of signal strengths in traditional wireless systems like satellite, personal communication systems, etc. This one size fits all
approach should not be applied to WSNs as they have characteristics that are completely different from the traditional systems.

A typical radio link is primarily affected by the path loss encountered during its propagation and radio propagation models are created to determine the realization of path loss along with providing an accurate prediction of a transmitter’s coverage area and modelling of the distribution signals across various regions. It should be noted that every telecommunication link comes across a variety of terrains, paths, obstacles and atmospheric conditions. Limitations therefore exist when it comes to the formulation of exact loss found within a particular telecommunication system and represented by a specific mathematical equation. Consequently, various models are required to be formulated based on the forms of radio links as well as the various conditions under which they exist. Such radio propagation models depend entirely upon the computation of the median path loss for a link calculated to a specific probability of the occurrence of the various conditions under which a particular study is carried out.

Use of radio propagation models in wireless sensor networks have been researched over a significant amount of time. Majority of the research documents the use of propagation models in determining the strength exhibited by a signal in urban environments. In another study, the researchers studied the signal strength in a different light as the sensor nodes used in the research operated at a comparatively lower frequency and were deployed in a rural environment with sparse vegetation
Using a long-range node consisting of a tested range of 13 KMs, the researchers implemented a novel propagation model based on the conventional models described in this section. For the rural environment, the range of nodes were computed by measuring the received signal strength at fixed distances from the transmitter. Both the transmitting and receiving nodes were programmed via TinyOS wherein the former produced a simple stream of data that was four times per second and the latter logged the received signal strength to a connected laptop. The suburban testing of wireless sensor network was conducted via the construction of four nodes installed in the form of an ad-hoc network.

Another study details the importance of using RF propagation models for analyzing topology for monitoring of sandstorms, which are serious natural disasters in Middle East [39] To abate the environmental, financial and health related damages, the study utilized RF propagation models for the effective monitoring of origination and build-ups of sandstorms. Typically, sensor nodes were deployed in areas experiencing sandstorms, and data was collected and relayed to an administration center set up remotely. However often times, these sensor nodes got temporarily buried depending upon the intensity of the storm resulting in an increased path loss during the sandstorm period. The WSNs also reported constant disconnections. Both these issues were due to the dynamic changes in the topology and therefore the study set up WSNs to perform a topological analysis of the origination of sandstorms. The study analyzed four types of channels in the sandstorm environment namely air-to-
air, air-to-sand, sand-to-air and sand-to-sand. Using such diverse channels and performing a percolation based connectivity analysis, the study showed that for a comparatively shallower burial depth, the use of multiple types of channels significantly improved the connectivity. The study also reported that comparatively smaller density of sensors produced almost equivalent performance levels in comparison with a single communication medium such as terrestrial air channel. Thus, the topology analysis performed in this study indicates that WSN architecture can be effectively deployed for timely monitoring of sandstorms.

**Free space path loss model**

An electromagnetic wave generated from a line-of-sight path passing through an area of free space such as air with no interferences to cause any reflection or diffraction displays a loss in the strength of its signal, referred to as the free space path loss (FSPL) and is expressed in decibels. The standard definitions of terms for antennas per IEEE Standard defines free space path loss as “The loss between two isotropic radiators in free space, expressed as a power ratio.” In terms of decibels, the free space path loss model can be denoted as follows:

\[
FSPL (dB) = 20 \log_{10} (d) + 20 \log_{10} (f) + 92.45
\]

(7)

Where:

- \(d\) is measured in KM and denotes the distance from the transmitter.
- \(f\) is the frequency of the signal measured in GHz.
In practical case scenarios, a physical environment can never be devoid of obstacles and therefore reflection or diffraction of radio waves is observed [18]. Consequently, the FSPL model is regarded as being fairly optimistic in cases involving near ground propagation as commonly observed in the different outdoor WSN applications [1].

A link budget equation that accounts for the gains as well as the losses incurred in the journey from the transmitter to the receiver, could be used to explain the attenuation of the transmitted signals. A link budget equation is denoted as:

Received Power = Transmitted Output Power + Transmitter Antenna Gains – Transmitter Losses

Logarithmically, this equation could be expressed as follows:

\[ P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_{M} + G_{RX} - L_{RX} \]  

(8)

Where:

- \( P_{RX} \) is the power received.
- \( P_{TX} \) is the power output of the transmitter.
- \( G_{TX} \) is antenna gain of the transmitter.
- \( L_{TX} \) is the transmitter losses.
- \( L_{FS} \) is the path loss.
- \( L_{M} \) is miscellaneous losses.
- \( G_{RX} \) is receiver antenna gain.
- \( L_{RX} \) is receiver losses.
Due to its theoretical and basic approach, the free space path loss is adopted by several research studies. A study made use of the free space path loss modelling approach in their research pertaining to precision agriculture [16]. The study made use of the open space, acting as Line of Sight (LoS), provided by the agricultural fields as well as the solar energy in proposing a unique WSN. The WSN made use of the existing radio frequencies as well as free space optical link model and hybrid source of energy for the base station. A flooding algorithm was developed that utilized the sensor location information to detect the farthest node for the purpose of transmitting energy. This helped in creation of positioned sensors as against the randomly placed sensors thereby covering maximum field area at the expense of minimum amount of energy, thereby making the system cost efficient.

A study analyzed a clustered form of wireless sensor network model which was based on the log-distance path [16]. The research modeled the inside of a cluster via the use of free space propagation model for distances that were lesser than the crossover distance and the log-distance path loss model having a loss exponent greater than 2 for distances that were greater than the crossover distance. The study made use of the FSPL model to determine the number of clusters required for limiting the energy spent in clustered wireless sensor network, given the geometry of the network, the number of nodes within the network, the cross-over distance and the data compression. Researchers have utilized the free space propagation model in determination of relationship between the percentage of energy consumed and the
number of hops required for a WSN which was equidistant and deployed linearly [24]. The model determined the critical number of hops after which no significant amount of energy saving was observed primarily due to the saturation of transmission power. In another study the researchers utilized the FSPL model in determination of adaptive transmit power scheme for WSNs [40]. The researchers used the model to develop an adaptive transmit power scheme based upon S-MAC, known as Adaptive Transmit Power MAC. Using this, they were able to effectively measure the distance between the sender and the recipient based on the amount of power received. Using this value, the research adaptively determined the transmit power level based on the propagation model and distance. Along with the two-ray ground reflection propagation model, the free space propagation model was used to create simulations for testing the performance of the proposed system and determine if it can reduce energy consumption significantly as compared to S-MAC.

An experimental analysis was performed that studied the path loss exponent observed in wireless sensor networks [27]. The study underscored the importance of the path loss component which is regarded as a vital characteristic of a wireless sensor network. The experiment was set up and conducted over three completely different environmental settings namely concrete, free space and industrial. The study calculated the received signal strength indicator (RSSI) depending upon the various channels and was derived as a function of the distances used for determining the RSSI and the standard deviation of log normal shadowing. The study reported a
path loss exponent between 1.57 – 1.94, 1.80 – 1.95 and 2-3 for concrete, free space and industrial environments respectively. The results of the experiment clearly demonstrated that there was a proportionate increase in the range of the measured path loss exponent as the free space existing within the environment became correspondingly lesser.

In a similar study, experimental path loss models primarily from the aspect of conserving energy, very vital in wireless sensor networks, were studied [41]. The study analyzed the effects on transmission distance caused due to the changing of the transmission power as well as the baud rate. For calculation purposes, the study utilized the Shannon channel capacity formula coupled with the log-distance path loss model and showed that the transmission distance is directly proportional to the transmitting power and the baud rate. The study brought forth the fact that multi-hop routing along with clustering algorithms can lead to an increase in conserving power at each sensor note. Apart from conserving power, an accurate level of transmitting power resulted in a significant lowering the levels of interference in the network as comparatively lesser motes in the surrounding environment were able to listen to the conversation. The study also noted that an increase in the network capacity due to the transmission of packets is confined to a comparatively smaller local area, with the other motes that are outside of the area, being free to transmit on their own.

A study demonstrated the increasing importance of wireless sensor networks for indoor as well as outdoor applications for various topologies and environments [16].
The study utilized a clustered topology wherein the network was grouped into nodes known as clusters and presented an energy model by modeling the sensor node transmission energy as a total of constant electronic energy and an amplifier energy proportional to the transmitter. Thus, the researchers modelled communications inside of a cluster via the use of free space propagation model involving distances that are lesser than a crossover distance, with a log-distance path loss model having a loss exponent of more than 2, for distances greater than the crossover distance. The simulations performed in the study were used to calculate the optimum number of clusters required for bringing about a significant decrease in energy expended by a clustered wireless sensor network and deemed as functions of network geometry, number of nodes, data compressed and the crossover distance. The simulations performed during the course of this research indicated that the optimum number of cluster heads become lesser as the data compression ratio becomes higher. For a given network geometry for a specific number of nodes, the study indicated that the optimum number of cluster heads are dependent on the crossover distance as well as the non-linear compressions. Thus, for a specified crossover distance, the optimum number of cluster heads were found to decrease with an increase in the compression ratio.
Two Ray Ground Reflection Model

A two-ray ground reflection model is used for predicting the path loss that occurs when the recipient signal consists of two components namely the Line of Sight denoted by LoS and the multi-path component that is created primarily by a single wave reflected off the ground. Thus, the two ray ground reflection model could be regarded as consisting of two paths. The first is the direct path whereas the second path is the ground reflected path. Research studies have shown that the two-ray ground reflection model provides a more accurate prediction at a long distance as compared to that of free space model [47]. The equation shown below is used to accurately predict the power received at distance $d$.

$$P_r(d) = P_t * G_t * G_r * h_t^2 * h_r^2 / d_L^4$$ (9)

Where:

$h_t$ and $h_r$ denote the heights of the transmitting and receiving antennas respectively.

However, for short distance, this model is not as effective as the free space propagation model due to the oscillations that are created due to the constructive and the destructive combinations offered by the two rays as seen in Figure 5 below. In logarithmic terms, the following equations expresses the two-ray ground reflection model and the associated path loss.

$$P_{rdBm} = P_{tdBm} + 10\log_{10} (G h_t^2 h_r^2) - 40\log_{10}(d)$$ (10)
Using equation xx above, we can calculate path loss as follows:

\[
Path\ loss = P_{t dBm} - P_{r dBm}
\]

\[
= 40 \log_{10}(d) - 10 \log_{10}(G h_t^2 h_r^2)
\]

(11)

Where, \(h_t\) and \(h_r\) denote the heights of the transmitting and receiving antennas respectively and \(P_r\) and \(P_t\) are the received and transmitted power respectively.

![Diagram of a two-ray ground reflection](image)

**Figure 5: Depiction of a two-ray ground reflection**

In terms of practical application, Lu outlines a linearized unified path loss formulation based on the two-ray ground reflection model [34]. The research incorporates the practical concerns associated with the formulation, thereby making it useful over different types of terrains and over a wide range of propagation effects.
The study, thereby extended upon the use of a two-ray ground reflection model by applying it to the communication nodes for platforms existing at high altitudes, unmanned air vehicles, ground terminals, and sensor and portable nodes. In terms of terrains, the study encompassed a wide variety and included urban, suburban, open, rural, foliaged, mountainous, and fresh and sea water, etc. The results obtained from the experimental set-ups illustrated the variance of path losses with the corresponding operating frequencies calibrated for different antenna heights and ranges. The findings of the study demonstrated the versatility of the two-ray ground reflection model as was evidenced in its use for providing more practical representation of the path loss characteristics. The findings of the study not only highlight the versatility of the two-ray ground reflection model but also the fact that it can be efficiently used in military as well as commercial applications.

The efficiency of two-ray ground reflection model is further validated by a study wherein the researchers compared and analyzed single and multiple mobile events WSNs via the use of Ad hoc On-Demand Distance Vector or AODV protocol and a two-ray ground reflection model [28]. Good put as well as routing efficiency metrics were taken into consideration for the evaluation of the performance of the wireless sensory networks. The research focused on 2-D networks, even though the researchers maintain that identical results would be obtained for more general 3-D network protocols. The research also made an assumption that MAC protocol outlined per the IEEE802.15.4 standard was the reference point for comparing with
other protocols. The study required that the recipient of each sensor node should receive data bits correctly which could be determined if the power received at the node exceeded the threshold limits set at the receiver denoted. For determining the parameters to be tested, the researchers used the commercial device – MICA2 OEM as a reference. Despite the fact that the received power at a given distance was found to be the same for all directions in a plane, the findings of the study indicated that the two-ray ground model was more accurate. The researchers attributed this finding to the fact that the model took into consideration not only the direct ray originating from the transmitter but also accounted for the signal reflected from the ground.

**Log-distance path loss model (LDPL)**

The radio propagation model known as the log-distance path loss model is designed for making accurate predictions in terms of calculating the path loss encountered by a signal inside of a building or areas with dense population per unit distance travelled. The term path loss refers to the decrease in the density of the power of an electromagnetic wave as it travels through space. Path loss could be regarded as an important element that can play a vital role in the analysis and the design of the link budget of a communication system. The equation below can be used for expressing log-distance path loss model.

\[
PL = P_{Tx} - P_{Rx} = PL_0 + 10 \gamma \log_{10} \frac{d}{d_0} + X_0 \quad (12)
\]
Where,

- $PL$ denotes the total path loss and is expressed as decibels.
- $P_{TxdBm}$ equates to $10 \log_{10} \left( \frac{P_{Tx}}{1\text{mW}} \right)$ and denotes the power transmitted in $dBm$, where $P_{Tx}$ is the power transmitted in watt,
- $P_{RxdBm}$ equates to $10 \log_{10} \left( \frac{P_{Rx}}{1\text{mW}} \right)$ and denotes the power received in $dBm$, where $P_{Rx}$ is the power received in watt,
- $PL_0$ denotes the path loss at distance $d_0$ and is expressed in decibels,
- $d$ denotes the path length,
- $d_0$ denotes the distance used as reference,
- $\gamma$ denotes the path loss exponent,
- $X_9$ denotes the normal random vehicle, and
- $\sigma$ denotes the standard deviation expressed in terms of decibels.

Wireless sensor networks typically guarantee a fine-grain monitoring in a broad range of deployment environments. Such deployment environments can fall in a variety of classes ranging from indoor residential to outdoor sandy habitats and could often times be harsh for achieving a wireless communication. From a network’s perspective, the efficiency depends upon the network’s performance in terms of delivering packets [28] This performance is dependent on the spatio-temporal characteristics of the packet loss as well as the reliance of the network on the
environment. In the research study by [28], the authors present a systematic measurement involving close to sixty nodes in three diverse deployment environments namely an indoor office building, a medium-foliage habitat and an open-air parking lot. The results of this extensive study brought forth the existence of gray areas inside of the communication range of the wireless sensor network and demonstrated an asymmetric pattern in the real world environment.

The application of this path loss model was adequately demonstrated in the study by wherein the researchers derived an empirical path loss model for wireless sensor network deployment in an artificial turf environment [3] The model was created based on the data collected from physical deployment and the model derived was compared with those for similar deployments in other terrains including sparse tree and long grass. The data collection procedure constituted the collection of RSSI at 128 points with 300 samples for each point. The RF measurement of each point was thereby an average of 300 RSS samples with all the measurements being made on a laptop connected directly to the receiving node. The readings recorded for path loss were compared with path loss predictions as derived from two empirical and two theoretical path loss models. The study reported a significant amount of differences in these signal prediction models. In terms of the path loss values for various environments, the values were found to be substantially dissimilar which was attributed to the dissimilarities existing in the wireless channel. The study highlights
the importance of collecting data in field as well as studying the radio frequency propagation for a variety of outdoor WSN deployments.

Along the lines of the previous study, another experimental set up examined the empirical path loss model for a WSN deployment in a sand terrain environment [4]. The model derived from the study was compared with the models obtained from long grass and sparse tree environments. The data collection procedure differed from the previous study wherein the data was collected on a sandy terrain at a local beach as against an artificial turf used previously. The data was collected at 128 measurement points with 300 samples studied for each point. The path loss as well as the proposed model for a sand terrain were compared to the parameters of path loss and empirical models of sparse tree and long grass environments and significant differences were reported.

A study derived received signal strengths at 868, 915 and 2400 MHz making use of RF hardware and running the simulations on Matlab for forest and plantation environments consisting of Mango and Guava cultivation [10]. The researchers used omnidirectional antennas which were at a height of 1m from the ground level and calculated the path loss, vegetation water content as well as values for cumulative distribution function. The study reported that the RSS values were higher at 2400 MHz as compared to those recorded at 869 and 915 MHz indicating that services or applications at that frequency could be used for applications involving high data rate and in environments characterized with several dense obstacles. In a similar study
the researchers observed RF propagations in agricultural fields and gardens for wireless sensor communications [17]. The study involved the received signal strength at ISM band at a frequency of 2.4 GHz in agricultural environment consisting of corn, paddy and groundnut fields and garden environment consisting of coconut garden with grass and an open lawn with dry and wet grass. The study measured the pat loss as well as the path loss exponent that corresponded with the root mean square error values that were derived from the received signal strengths measured from different positions. The study reported an increase in the path loss values with a corresponding increase in the vegetation depth. The researchers attributed this path loss to dense vegetation that was obstructing the line of sight between the receiver and the transmitter. In a similar study, the researchers validate these findings via the use of RF propagation measurements in plantation and forest deployment environments [46]

Thus, similar to the findings of the studies mentioned above, another study derived the values derived for the equation (xx) have shown that the path loss exponent can have a value of 2 corresponding to a free space environment and between 4 and 6 for an indoor environment characterized by obstructions [26] Nonetheless, in a path loss model, the role of the path loss exponent is very vital in analyzing a wireless sensor network and could be used to determine the propagation[35] In case of cellular systems that cover a larger and wider area, a distance of 1 KM could be regarded as standard reference distance as used in most studies involving the use of these models
Studies comparing have reported that compared to the free space path loss and two-ray models, the log-distance path loss model is more precise in determining the path loss observed in a wireless sensor network [36]. The path loss model also makes up for the lack of a robust model for accurately determining the path loss seen in a particular wireless sensor network. Consequently, the log-distance path loss model is used due to its simplicity and its ability to adjust the same to real life measurements.

**Wireless technology and radio standards for wireless sensory networks**

Created by IEEE802.15 working group, IEEE802.15.4 is a standard that details the physical layer as well as the media access control concerning the low-rate wireless sensor networks. The protocol provides a foundation for network specifications including ZigBee that extends this standard further via the development of upper layers not outlined in 802.15.4. The physical layer could be regarded as the underlying layer that allows for transmission of data along with facilitating an interface to allow for management and access of each individual functions. The physical layer also plays a vital role in maintenance of an information database for related sensory area networks. Therefore, the physical layer could be said to manage the radio-frequency transceiver while also performing the job of selecting channels and managing signal and energy functions.
Another important aspect of this protocol is that of MAC layer or the medium access control layer that helps in the transmission of the MAC frames via the utilization of the physical channel. Apart from the data service, the MAC layer provides a management interface and plays a vital role in the managing of the access to the physical channel and the network. The MAC layer also helps in the validation of control frames while provisioning slots of time and handling of associations at the sensor nodes. Lastly, it provides for the hook points that are critical in the providing of secure services. It is important to note that the IEEE 802.15 standard does not make use of the 802.1D or 802.1Q, thus not staying involved in the exchange of the standard Ethernet frames. This standard is designed based on the fact that most IEEE 802.15.4 physical layers primarily provide support to frames that are up to 127 bytes. Per this standard, the networks are designed in form of peer-to-peer and star networks. It should be however noted that each network requires a minimum of one full-functional device (FFD) in order to function as the network’s coordinator. Networks are therefore created via the use of devices that are grouped and separated from each other by adequate distances. Every device is characterized by a 64-bit identifier that is unique to it and in certain cases, a 16-bit identifier may also be used inside of a restricted environment. ZigBee network topology also forms an important and mentionable aspect of the wireless technology and radio standards for wireless sensory networks. It could be regarded as a specification required for a set of higher level communication protocols which are utilized to design personal area networks
created from low powered and comparatively smaller digital radios. ZigBee utilizes the IEEE 802.15.4 2003 standard specification for its physical and MAC layers and while the standard provides mesh, star, tree and cluster tree topologies, only star, tree and mesh topologies are supported by ZigBee.

Mesh network topologies, also known as peer-to-peer networks, are characterized by random connection patterns with their extension being simply limited by the distance between each pair of nodes. The peer-to-peer networks are designed so as to facilitate as the foundation for the ad hoc networks that possess the capability of being self-manageable while being easy to organize. However, because, the standard does not provide for a clear outline of a network layer, it does not support routing even though an additional layer could be added for providing support for the communications that involve multi-hops. The peer-to-peer networks also allow for easy addition of any topological restrictions as evidenced by the mention of the cluster tree structure per which a reduced function device (RFD) may only be associated with one FFD at any given time to design networks consisting of RFDs being the leaves of the cluster tree with majority of the nodes being FFDs. The standard allows for the extension of this network into a generic mesh network, the nodes of which consist of cluster tree networks and local and global coordinators for every cluster. A star pattern differs from a peer-to-peer network based on the fact that the network pattern is more defined with the central node acting as the network coordinator. A star patterned network can be designed in the event of an FFD deciding to create a personal area
network (PAN) for itself. It may even announce itself as being the coordinator and select a unique PAN identifier. Following this, other devices are able to join the network and are completely independent of other star networks.

In case of tree network topology, the network is characterized by the presence of a central node referred to as root tree which acts as a coordinator, numerous routers as well as end devices. The router plays the role in the extension of network coverage. The end nodes which are attached to the coordinator are known as children. Children could be had only by routers and the coordinators and consequently only these two can act as parents. An end device on the other hand, cannot have children and therefore cannot act as a parent. The cluster tree topology is an extension of the tree topology, wherein a parent in association with its children is referred to as a cluster and is assigned a unique cluster id. A cluster tree topology helps in offsetting the primary drawback of the tree topology, which is the non-functioning of the children in the event of a parent getting disabled. Additionally, in case of tree network topology, two nodes that are in geographical proximity of each other are not able to communicate directly. This drawback is also overcome via the use of a cluster tree network topology.

The effective use of protocols outlined by the IEEE 802 standards is demonstrated in a study wherein the researchers developed a distributed software system for a WSN [5]. The purpose of this software system was to remotely monitor the effects that hurricane winds have on man-made buildings. The software developed was
appropriately segmented so as to separate the codes used for application and communication modules of the software. The use of the IEEE 802 standards in the design of this software interface could be attributed to the versatility demonstrated by the software as its structure, features, and functionalities could be applied to WSNs that were deployed in a variety of harsh environments. A study evaluated the new RF models of a widely used simulator for wireless sensory network known as TOSSIM, which is known to simulate the source code for TinyOS, a simulator based on the IEEE 802.15.4 standard \cite{12}. Despite the fact that TOSSIM’s architecture as well as interfaces are suitable for WSNs based on IEEE 802.15.4 standards, the present RF model is too basic for providing support to the physical stack of IEEE 802.15.4. The research performed proposed a new wireless propagation model as well as RF physical stack based on the two-ray ground path loss model using a CC2420 RF transceiver. The new model was proposed in order to further improve the efficiency of the wireless simulation results while simultaneously implementing the IEEE 802.15.4 standard. The study brings forth the importance of the IEEE 802.15.4 standards in modelling the wireless sensor networks in terms of wireless communication and microelectronic technologies. In another such study, the researchers analyzed an indoor localization based on received signal strength indicator via the use of IEEE 802.15.4 standards for low powered wireless sensor networks \cite{7}. The study indicated that the IEEE 802.15.4 radio modules could be
applied to the sensory nodes to get their positioning information if the position as well as the number of reference nodes are provided.

**Summary**

There are several radio propagation models applicable to a wireless communication system that can be used for predicting the loss of signal strength as well as the loss of distance as a function of path. The three more widely used models are the free space propagation model, the two-ray ground reflection model and the log-distance model. The underlying assumption of a free space propagation model is that the transmitter and the receiver are present in the line of sight without the presence of any obstacles between the two. The two-ray ground reflection model is an extension of the free space propagation model wherein the model takes reflection into consideration. In this type of model, the rays are received by the receiver in two different ways namely via direct communication and reflection. The model is further simplified in the event of the distance being substantially more than the height of the transceivers, with the other variables being the same. Lastly, the log-distance model is derived based on the analytical as well as empirical methods and could be regarded as a radio propagation model designed for prediction of the path loss encountered by a signal due to obstruction such as those typically found in any densely populated area or a building.
Signal propagation shows significant variations depending upon the environment and it can be attenuated due to scattering, reflection caused due to the obstructions present in the way of its propagation. Consequently, it is necessary to adequately create and implement the appropriate radio propagation models to primarily address the issue of signal attenuation while simultaneously estimating the coverage of a wireless system’s radio signal. This dissertation aims at applying these principles and theories primarily to the signal obstructions caused by sand and dust storms that are known to occur at higher frequencies in the Middle Eastern countries which are characterized by a dessert climate and sandy terrain.
Chapter 4: Data collection

Introduction

This chapter provides the steps, test-bed, and data collection of the experiment’s process on several WSN deployment environments during sand and dust storms. The aims of this dissertation is get the effect of WSN in SDS environments and create propagation model in sand and dust storm. Then the engineers can develop the equipment to get an excellent signal without much path loss. To get these goals we divided the development process to several parts that are illustrated in Figure 6.

This chapter examines several specific wireless network propagation scenarios in the presence of dust storms. The attention is focused on propagation within 2.4GHz ISM band and on the scenario of Wireless Sensor Networks (WSN). The 2.4GHz ISM band is the most popular frequency band for deployment of unlicensed wireless systems. It extends from 2400-2483.5MHz and it is used worldwide for deployment of WiFi (IEEE 802.11 b, g, n), Bluetooth, Zigbee (IEE 802.15.4), and many other standard and proprietary technologies. This band also is one of the primary bands used for deployment of WSNs. These networks are typically deployed in the outdoor environment and therefore, they are exposed to the weather conditions. Also, they are deployed in configurations that are quite different than what is encountered in
other wireless systems. Unlike, for example cellular systems, WSN are deployed using low power devices, with low antenna heights and with omnidirectional patterns. For such deployments, there is a general lack of relevant propagation models. This is especially true for the circumstances where besides terrain and manmade obstructions, the signal encounters additional impairments coming from the effects of the sand storms.

Figure 6: Full WSN experiment process during sand and dust storm

The reminder of this chapter is organizes as follows. The first part explain how to create the WSN system by design the equipment. This section divided to tow part.
I. Collect the hardware and prepare it as a sensor. II. Configure the equipment and
install the RSSI, Temperature, humidity, pressure and wind speed code into Arduino hardware by X-CTU and Arduino software.

The second part is deploy the sensors in four different environment: clear sky, normal sand storm, dusty storm, and heavy sand storm. Then collect the real time data of RSSI, Temperature, pressure, humidity, and wind speed. Furthermore, get path loss values include path loss exponent reference distance path loss and compare the path loss model in each different environment during the sand storm.

The third part model the compression data to generate the path loss propagation model during sand and dust storms. The path loss reorganization needs improvement to get better signal for users. Users are spending more time to communicate with others during sand storm. The engineers can develop the sensors to have the best technology for running high signal as well as that enable connect without interruption.

**WSN Deployment Environment**

Four WSN deployment environments during sand storm in Riyadh city have been selected to collect real time RSSL, Temperature, pressure, humidity, and wind speed
measurements in concert surface and sand terrain in clear sky, normal sand storm, dusty storm, and heavy sand storm environments.

**Experimental Setup**

This section introduces the steps used in the experiments. To get real time RF propagation conduct during sand and dust storms deployment scenarios of WSN we must get the RF measurements in each different environment during sand and dust storms. The real data helps to understand the WSN conduct in SDS which are important source of information.

The following setup are described the system on deployment of wireless sensor nodes and the equipment used within the thesis work. These setups are explained to give some helpful to the engineers who will work with this or similar systems in the future.

**System Description**

To understand the huge path loss effect of Wireless network communications in SDS we have to go through a brief sand and dust storms and deploy the system on real sand environment. It is also necessary to design the system to work perfectly and provide all of the support to protect the sensors from the sand and wind damage.

A diagram of the measurement system is presented in Figure 7 as seen, the system consists of
1. WSN transmitter. The WSN transmitter consists of an Arduino board and with the Xbee PRO 2 radio [42]. The interface between the Arduino board and the Xbee transmitter is provided through the Arduino shield. Additionally, the Arduino board at the transmitter is connected to a sensor board called Weather shield and to an external anemometer.

The principle component for management of the transmitter is the Arduino board. The Arduino runs the software that collects the data from the Weather shield and the anemometer. The data are then forwarded to Xbee PRO 2 radio and sent over to the receiver side. Unlike environmental parameters the Received Signal Level (RSL) measurement is performed by the Xbee receiver. This measurement is used as the principle measurement for estimation of the propagation path loss between the Xbee transmitter on the remote unit and the Xbee receiver at the base unit.

2. WSN receiver. The WSN receiver may operate in two different modes. The first mode is a stand-alone mode. In this mode, the receiver consists of an Arduino board, Arduino shield and Xbee Pro 2 radio. When the receiver is operating in a stand-alone mode, the data received by the Xbee radio are stored locally on a memory card that resides on the Arduino board. The stand-alone mode allows the system to operate in a severe sand storm, and it was used for most of the measurements. After the measurement session, the
data stored on the memory card are uploaded onto the laptop for further processing.

Alternatively, the receiver may be configured to operate without the Arduino board. This mode is referred to as the connected-mode. In the connected mode, the Xbee radio is connected to a laptop through an interface board Xbee explorer. In this mode, the data are stored directly to the laptop. When in connected mode, the user may monitor the data collection process on the laptop screen. However, this is only feasible in clear sky conditions.

3. Collection laptop. Collection laptop hosts software that is utilized for configuration of the measurement system and for the analysis of the data. Two software environments are used. Software X-CTU is used for configuring the Xbee radios and for formation of the WSN. The receiver Xbee radio is configured as the 802.15.4 network coordinator, while the transmitter unit is configured as a remote. The second software environment is the Arduino board IDE. This software is used to program the Arduino board of the transmitter and the Arduino board of the receiver in the connected mode. In the standalone mode, the receiver does not use Arduino board and data are read directly from the Xbee receiver.
Figure 7: Block diagram of the measurement system

Wireless sensor nodes deployment
The SDS characterization system consists of remote sensor nodes installed on the concert surface sand terrain and communicating with a base unit. The base unit communicates with the field laptop, which collects and stores the individual installations data. It is essential to plan the positions of wireless sensor nodes in accordance with real life scenario. Therefore, throughout the experiment, the intent
was to place a transmitting node at the center of the designated deployment field and collect RSL readings at different distances and along different degrees, pressure, temperature and wind speed. Therefore, a sand & dust storm environment is needed to carry out all of the measurements and scenario experiment [10]. The experiments were divided into four parts, with each part having a different environment. The nods deployed in at five different distances (i.e., 5, 10, 15, 20, and 25). The nods send the data to the transmitter which located at the center of the designated deployment to collect the real time more than 1000 path loss measurements that were obtained across 8 different radials and 5 different radial distances.

**System equipment and system requirements**

This part describe the system requirements and shared requirements for the Sand and dust storm characterization system components, including hardware requirements for tagging and software requirement. Functional requirements consist of (XBee radio, XBee explorer, XBee Arduino shield, Arduino, Field laptop, pressure and temperature sensor, and Anemometer). The software requirement consist of (Radio firmware configuration and XBee Arduino). WSNs need to apply the following steps:

1] Support sensor nodes in SDS scale deployment scenarios.

2] The collection of measurements required for characterization of WSNs in SDS environment requires temperature, pressure, wind speed and wind direction and RSL.
3] Reliable storage for experiment reading data.

4] Collect the sampling rate at least 40 sample/sec and transmission rate to the filed laptop every 30 Sec.

**Hardware description**

To applied the WNS application system during SDS. This section offer an introduction of the functional requirement to address the needs of WNS.

1. XBee radio

There are lots of different types of XBee Radio modules like series1, series 2, and series 2B, Series 2 pro. There are more difference antenna for XBee radios like Whip antenna, wire antenna, chip antenna, PCB antenna, U.FL connector, and RPSMA connector as seen in Figure 9 Freescale made the Series 1 that use to provide simple, standards based point to point communications. The Series 2 PRO use a microchip from Ember Networks that allow different standards based ZigBee mesh networking and has more power and larger transmission range than the regular one. We used XBee S2 pro with wire antenna it in the system as seen in the Figure 8 [42].
2. **XBee explorer**

This unit is small microchip made by Digi XBee to program the XBee modules by plug the XBee explorer to the laptop using mini USB to a standard USB 2.0
port. The XBee Radio connects to the XBee explorer as seen in Figure 11 which allow to configure the XBee radio by X-CTU software to configure XBees as a coordinator or router for connection and pass data between the computer and nods for the desired application X-CTU software seen in Figure 17. The XBee explorer can be seen in Figure 10.

Figure 10: XBee explorer
3. XBee Arduino shield

The XBee Arduino shield is an interface connects the XBee radio to the Arduino board and get the data from XBee to Arduino board The Arduino board can utilize the XBee radio and communicate wirelessly using ZigBee [54] The XBee Arduino shield can be seen in Figure 12.
4. Arduino

The Arduino is a microcontroller board. The microcontroller is a specialized computer that can be optimized to do a specific job using Arduino software to program it with specific code. The Arduino software seen in figure 21. For our application, the Arduino will be taking input data from the sensors and will transmit them wirelessly using ZigBee. The Arduino board can be seen in Figure 13.
5. **Field laptop**

The most important steps of the filed laptop:

a) Configures the Xbee radios by X-CTU software.

b) Program the Arduino board by Arduino software.

c) Records and stores the data transmitted by the sensor nodes.

The field laptop can be seen in Figure 14.

![Field laptop connecting with unit unite](image)

**Figure 14**: Field laptop connecting with unit unite

6. **pressure and temperature and humidity sensor**

There are many kind of sensors. Each one has specific work like getting torture reading, humidity, pressure, density, and wind speed etc. We used Weather
Shield because it is an easier one to use Arduino shield to get pressure, humidity, and temperature in the same time [55]. The weather shield can be seen in Figure 15.

![Weather Shield](image)

**Figure 15: Weather Shield (Temperature& humidity& temperature sensor)**

7. **Anemometer**

This sensor device is used to measure wind speed and direction. The sensor is connected to the sensor node, and the collected data is transmitted wirelessly using the XBee radio and ZigBee communication protocol. Arduino board coded to get the wind speed data from Anemometer. The Anemometer can be seen in Figure 16.
Software description

To applied the WNS application system during SDS. This section offer an introduction of the software requirement to address the needs of WNS.

1. Radio firmware configuration

Configuration interface of the radios is made through UART connection. Hence, configuration of all radios was done by using a UART API software installed on an x32 or x64 Intel Architecture computer with Windows OS, in order to download the firmware, set variables, and to update them according to the desired conditions. Radio’s firmware communication can be made through Serial Terminal, or using a dedicate GUI User friendly software that allows us to download and update all the firmware’s variables and parameters, without the need of execution of Serial terminal
AT command. The software used was X-CTU, and configuration was done by following these steps:

A. Plug Radio shield with Xbee explore in the laptop by using mini UBC cable.
B. Open X-CTU program seen in Figure 17.

![X-CTU Modem Configuration tab](image)

**Figure 17: X-CTU Modem Configuration tab**

C. For a basic unit we make the radio shield as a coordinator and the rest as a router and let them communicate to each other by using AT command.

I. For a coordinator we click Read button in the program to access the radio’s setup then we change the PAN ID which we have it in the back of
the router radio shield and change the high and low destination address to as seen Figure 18.

Figure 18: The configuration of the destination address in X-CTU

Figure 19: Using XBee Radio
II- For the Router we have to let them in the same PAN ID which in the back of the XBee radio’s coordinator and the destination high and low address. The PAN ID seen in Figure 19.

D. Test the communication between them by using terminal window in X-CTU as seen in Figure 20.

![Figure 20: X-CTU terminal tab](image)

2. **XBee Arduino shield firmware**

A. To connect to Arduino board we plug it into a computer using a USB A-to-B-style cable.

B. Select the XBee model for XBee Arduino board from the Board menu.

C. Select serial 2 port from the Serial menu.
D. It is ready to program the code which measure the temperature and presser and wind speed as seen in Figure 21.

![Arduino IDE programming software](image)

**Figure 21: Arduino IDE programming software**

**Deploy the sensor and collect the data**

The measurements of the path loss are performed on a regular grid as presented in Figure 22. The receiver is placed in the center of the grid and the transmitter is moved between measurement points. The measurement points are placed on eight radials.
The angle between the radials is 45 degrees. There are 5 measurement points at each radial. On a given radial, the measurement points are spaced 5 meters apart. The closest one is 5 meters from the receiver, and the furthest one is 25 meters away. Several hundreds of path loss measurements are collected for each measurement point. The measurements at a single point are averaged to yield one path loss measurement value. In a given experiment, the path loss is obtained for each measurement point. Therefore, the experiment consists of thousands path loss measurements that were obtained across 8 different radials and 5 different radial distances.

![Figure 22: Location of the measurement points in data collection process](image)
Deploy the WSNs on the sand and dust storm

The sensors were deployed in open space in the city of Al-Kharj located in Riyadh and frequented by high intensity sand and dust storms. The RSSI, temperature, pressure and wind speed data was collected from the sensors which were positioned along five points at an interval of 5 meters (i.e. 5m, 10m, 15m, 20m and 25m). Eight radials were also positioned at an angle of 45° between them. Using this experimental set up, several thousand data points were recorded. For each sampling point, 380 samples were collected within a duration of 30 seconds. The RF measurements obtained at each of these 40 sampling points was an average value of the RSS samples. All RF measurements were recorded and saved to a laptop that was directly connected to the receiving node containing a log of temperature, pressure, humidity and wind speed values.

Collect the real time data and experimental result

Measured data are collected in four experiments. The experiments are defined on the basis of the sand storm severity. In the first experiment, the data are collected under a clear sky. This experiment is used as the baseline. The remaining three experiments are dusty sky, sand storm and heavy sand storm experiments.

The path loss is calculated from known Effective isotropic Radiated Power (EiRP) and measured Received Signal Level (RSL). That is:
\[ P_L[dB] = EiRP[dBm] - RSL_{min}[dBm] \]  \hspace{1cm} (13)

Where, \( P_L \) is the propagation path loss expressed in \( dB \), \( EiRP \) is the effective radiated power expressed in \( dBm \) and \( RSL_{min} \) is the received signal level expressed in \( dBm \).

The \( EiRP \) of XBee Pro 2 transmitter is 63 \( mW \) (18 \( dBm \)). The antenna at the receiver is an omnidirectional antenna with the gain of 0 \( dB \).

1. **Clear sky**

The RSS measurements were obtained in morning hours and outside of Al-Kharj city in clear sky. Table 2 shows RSL averaged values then we convert them into path loss by equation (13):

During measurements, the wind speed was very low and therefore, the presence of the sand within the air was at its minimum. The conditions for this experiment are illustrated in Figure 23. As seen, the area is very flat with approximately the same propagation conditions in all directions from the receiver (i.e. along any of the radials). The path loss values obtained for 40 measurement points are shown in Table 3. Figure 24 represents the fitting line of the average path loss.
Figure 23: Clear sky environment

Table 2: Average RSL measurements in clear sky

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
<th>20m</th>
<th>25m</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0°</td>
<td>-50.71</td>
<td>-67.78</td>
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<td>-71.96</td>
<td>-71.28</td>
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<tr>
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<td>45°</td>
<td>-55.23</td>
<td>-61.22</td>
<td>-65.16</td>
<td>-70.81</td>
<td>-71.34</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
<td>-53.78</td>
<td>-62.23</td>
<td>-67.36</td>
<td>-72.29</td>
<td>-74.36</td>
</tr>
<tr>
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<td>135°</td>
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<td>-68.15</td>
<td>-70.18</td>
<td>-76.26</td>
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<tr>
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<td>180°</td>
<td>-57.02</td>
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<td>-74.81</td>
<td>-77.81</td>
<td>-75.73</td>
</tr>
<tr>
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<td>-73.01</td>
</tr>
<tr>
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<td>270°</td>
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<td>-65.03</td>
<td>-72.20</td>
<td>-69.79</td>
<td>-74.45</td>
</tr>
<tr>
<td>8</td>
<td>360°</td>
<td>-54.39</td>
<td>-60.98</td>
<td>-77.27</td>
<td>-76.73</td>
<td>-72.13</td>
</tr>
<tr>
<td>Average RSL [dBm]</td>
<td></td>
<td>-55.14</td>
<td>-63.84</td>
<td>-70.82</td>
<td>-73.27</td>
<td>-73.57</td>
</tr>
</tbody>
</table>
Figure 24: Measured versus predicted path loss for clear sky

Table 3: Average path loss measurements in clear sky

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5 m</th>
<th>10 m</th>
<th>15 m</th>
<th>20 m</th>
<th>25 m</th>
</tr>
</thead>
<tbody>
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<td>0°</td>
<td>70.21</td>
<td>87.28</td>
<td>86.69</td>
<td>91.46</td>
<td>90.78</td>
</tr>
<tr>
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<td>45°</td>
<td>74.73</td>
<td>80.72</td>
<td>84.66</td>
<td>90.31</td>
<td>90.84</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
<td>73.28</td>
<td>81.73</td>
<td>86.86</td>
<td>91.79</td>
<td>93.86</td>
</tr>
<tr>
<td>4</td>
<td>135°</td>
<td>74.54</td>
<td>80.67</td>
<td>87.65</td>
<td>89.6</td>
<td>95.76</td>
</tr>
<tr>
<td>5</td>
<td>180°</td>
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<td>88.80</td>
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<td>76.52</td>
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<td>93.9</td>
<td>96.06</td>
<td>92.51</td>
</tr>
<tr>
<td>7</td>
<td>270°</td>
<td>77.43</td>
<td>84.53</td>
<td>91.70</td>
<td>89.29</td>
<td>93.95</td>
</tr>
<tr>
<td>8</td>
<td>360°</td>
<td>73.89</td>
<td>80.48</td>
<td>96.77</td>
<td>96.23</td>
<td>91.63</td>
</tr>
<tr>
<td>Average path loss (dB)</td>
<td></td>
<td>74.64</td>
<td>83.34</td>
<td>90.32</td>
<td>92.77</td>
<td>93.07</td>
</tr>
</tbody>
</table>
The average environmental conditions recorded during the clear sky experiment are presented in Table 4.

**Table 4: Environmental conditions during the clear sky measurements**

<table>
<thead>
<tr>
<th>Humidity (%)</th>
<th>Temperature (°C)</th>
<th>Pressure (mbar)</th>
<th>Wind speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.1</td>
<td>33.7</td>
<td>1060</td>
<td>2.3</td>
</tr>
</tbody>
</table>

2. **Sand storm**

An image of an area with a sand storm is presented in Figure 25. The visibility is lower than in the case of dusty sky. Table 5 shows RSL averaged values. The measured path loss for the sand storm are presented in Tables 6. Figure 26 represents the fitting line of the average path loss.

![Figure 25: Sand storm environment](image)
Table 5: Average RSL measurements in sand storm

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
<th>20m</th>
<th>25m</th>
</tr>
</thead>
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<tr>
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<td>0°</td>
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<td>-76.74</td>
<td>-85.60</td>
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<tr>
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<td>-78.19</td>
<td>-83.44</td>
<td>-83.93</td>
</tr>
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<tr>
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<tr>
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<td>-85.66</td>
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<td>8</td>
<td>360°</td>
<td>-63.48</td>
<td>-69.04</td>
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</tr>
<tr>
<td>Average RSL [dBm]</td>
<td></td>
<td>-61.47</td>
<td>-67.83</td>
<td>-78.35</td>
<td>-82.53</td>
<td>-85.40</td>
</tr>
</tbody>
</table>

Figure 26: Measured versus predicted path loss for sand storm

\[ y = 36.085x + 54.346 \]
Table 6: Average path loss measurements in sand storm.

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
<th>20m</th>
<th>25m</th>
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</thead>
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<td>93.84</td>
<td>96.24</td>
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</tr>
<tr>
<td>Average RSL [dBm]</td>
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<td>87.33</td>
<td>97.85</td>
<td>102.02</td>
<td>104.89</td>
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</tbody>
</table>

The average environmental conditions recorded during the sand storm sky experiment are presented in Table 7.

Table 7: Environmental conditions during the sand storm measurements

<table>
<thead>
<tr>
<th>Humidity (%)</th>
<th>Temperature (C)</th>
<th>Pressure (mbar)</th>
<th>Wind speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.6</td>
<td>34.7</td>
<td>959</td>
<td>13.6</td>
</tr>
</tbody>
</table>

3. Dusty storm

An image of a dusty sky deployment is presented in Figure 27. As it may be seen the wind lifts some of the sand particles. As a result, the visibility throughout the area is decreased. The presence of the sand in the air affects the propagation of the signal. Table 8 shows RSL averaged values. The path loss data obtained
during the dusty sky are presented in Table 9. Figure 28 represents the fitting line of the average path loss.

![Figure 27: Dusty sky environment](image)

Table 8: Average RSL measurements in dusty sky

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
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<th>25m</th>
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<td>-58.44</td>
<td>-74.96</td>
<td>-84.77</td>
<td>-87.72</td>
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<td>-77.30</td>
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<td>5</td>
<td>180°</td>
<td>-68.50</td>
<td>-74.90</td>
<td>-76.55</td>
<td>-76.98</td>
<td>-77.82</td>
</tr>
<tr>
<td>6</td>
<td>225°</td>
<td>-62.07</td>
<td>-69.02</td>
<td>-75.22</td>
<td>-85.87</td>
<td>-89.00</td>
</tr>
<tr>
<td>7</td>
<td>270°</td>
<td>-56.29</td>
<td>-61.64</td>
<td>-63.38</td>
<td>-74.79</td>
<td>-76.70</td>
</tr>
<tr>
<td>8</td>
<td>360°</td>
<td>-57.92</td>
<td>-62.14</td>
<td>-73.08</td>
<td>-72.89</td>
<td>-75.38</td>
</tr>
<tr>
<td>Average RSL [dBm]</td>
<td></td>
<td>-56.74</td>
<td>-65.89</td>
<td>-74.15</td>
<td>-77.08</td>
<td>-79.92</td>
</tr>
</tbody>
</table>
Figure 28: Measured versus predicted path loss for dusty storm

Table 9: Average path loss measurements in dusty storm

The average environmental conditions recorded during the dusty sky experiment are presented in Table 10.

Table 10: Environmental conditions during the dusty sky measurements

<table>
<thead>
<tr>
<th>Humidity (%)</th>
<th>Temperature (C)</th>
<th>Pressure (mbar)</th>
<th>Wind speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.8</td>
<td>45.7</td>
<td>974</td>
<td>13.0</td>
</tr>
</tbody>
</table>
4. Heavy sand storm

The heavy sandy storm deployed is illustrated in Figure 29. Table 11 shows RSL averaged values. The measurements obtained in this experimental scenario are presented in Table 12. Figure 30 represents the fitting line of the average path loss.

![Figure 29: Heavy sand storm environment](image)

### Table 11: Average RSL measurements in heavy sand storm

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
<th>20m</th>
<th>25m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>-66.00</td>
<td>-67.87</td>
<td>-71.04</td>
<td>-85.37</td>
<td>-88.95</td>
</tr>
<tr>
<td>2</td>
<td>45°</td>
<td>-65.73</td>
<td>-70.46</td>
<td>-71.65</td>
<td>-83.84</td>
<td>-86.46</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
<td>-65.58</td>
<td>-68.00</td>
<td>-60.70</td>
<td>-82.90</td>
<td>-87.70</td>
</tr>
<tr>
<td>4</td>
<td>135°</td>
<td>-67.50</td>
<td>-68.75</td>
<td>-70.83</td>
<td>-85.45</td>
<td>-89.29</td>
</tr>
<tr>
<td>5</td>
<td>180°</td>
<td>-66.53</td>
<td>-68.75</td>
<td>-70.80</td>
<td>-85.45</td>
<td>-86.29</td>
</tr>
<tr>
<td>6</td>
<td>225°</td>
<td>-68.50</td>
<td>-69.35</td>
<td>-70.65</td>
<td>-83.30</td>
<td>-90.90</td>
</tr>
<tr>
<td>7</td>
<td>270°</td>
<td>-65.29</td>
<td>-70.78</td>
<td>-70.78</td>
<td>-85.52</td>
<td>-90.52</td>
</tr>
<tr>
<td>8</td>
<td>360°</td>
<td>-65.88</td>
<td>-70.42</td>
<td>-71.26</td>
<td>-82.82</td>
<td>-90.26</td>
</tr>
<tr>
<td>Average RSL [dBm]</td>
<td></td>
<td>-66.37</td>
<td>-69.29</td>
<td>-69.71</td>
<td>-84.33</td>
<td>-88.79</td>
</tr>
</tbody>
</table>
Figure 30: Measured versus predicted path loss for heavy sand storm

Table 12: Average path loss measurements in heavy sand storm

<table>
<thead>
<tr>
<th>Radial No.</th>
<th>Degree</th>
<th>5 m</th>
<th>10 m</th>
<th>15 m</th>
<th>20 m</th>
<th>25 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>85.5</td>
<td>87.37</td>
<td>100.54</td>
<td>104.87</td>
<td>108.45</td>
</tr>
<tr>
<td>2</td>
<td>45°</td>
<td>85.23</td>
<td>89.96</td>
<td>101.15</td>
<td>103.34</td>
<td>105.96</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
<td>85.08</td>
<td>87.50</td>
<td>90.20</td>
<td>102.40</td>
<td>107.20</td>
</tr>
<tr>
<td>4</td>
<td>135°</td>
<td>87.00</td>
<td>88.25</td>
<td>100.33</td>
<td>104.95</td>
<td>108.79</td>
</tr>
<tr>
<td>5</td>
<td>180°</td>
<td>86.03</td>
<td>88.25</td>
<td>100.30</td>
<td>104.95</td>
<td>105.79</td>
</tr>
<tr>
<td>6</td>
<td>225°</td>
<td>88.00</td>
<td>88.85</td>
<td>100.15</td>
<td>102.8</td>
<td>110.40</td>
</tr>
<tr>
<td>7</td>
<td>270°</td>
<td>84.79</td>
<td>90.28</td>
<td>100.28</td>
<td>105.02</td>
<td>110.02</td>
</tr>
<tr>
<td>8</td>
<td>360°</td>
<td>85.38</td>
<td>89.92</td>
<td>100.76</td>
<td>102.32</td>
<td>109.76</td>
</tr>
<tr>
<td>Average path loss (dB)</td>
<td>85.87</td>
<td>88.79</td>
<td>99.21</td>
<td>103.83</td>
<td>108.29</td>
<td></td>
</tr>
</tbody>
</table>

The average environmental conditions recorded during the heavy sand storm experiment are presented in Table 13.
Table 13: Environmental conditions during the heavy sand storm measurements

<table>
<thead>
<tr>
<th>Humidity (%)</th>
<th>Temperature (C)</th>
<th>Pressure (mbar)</th>
<th>Wind speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>6.1</td>
<td>984</td>
<td>23.3</td>
</tr>
</tbody>
</table>
Chapter 5: Modeling

This chapter provides the comparison path loss measurement which presented in the last chapter and proposes an empirical model for prediction of the radio path loss in Wireless Sensor Networks (WSNs). The model applies to WSNs that are deployed in environments with dust and sand storms. It is developed as a result of statistical analysis of the measured data collected during dust and sand storms. The proposed model shows a very good agreement with the measured data. It is also demonstrated that the radio path loss correlates very well with the wind speed. Therefore, the wind may be considered as a principle source that determines the severity of the dust and sand storms from the path loss standpoint.

Figure 31 shows the average path loss as a function of log of distance for the four experimental environments. In all cases, one may observe that the path loss follows log-distance model. That is, in the first approximation, the path loss may be estimated using the expression [4]:

\[ PL(d) = PL_0 + m \cdot \log_{10} \left( \frac{d}{d_0} \right) \]

Where:

- \( PL_0 \) is one meter intercept value expressed in dB
- \( m \) is the slope in dB/dec
- \( d \) is the transmitter/receiver separation
- $d_0$ is the reference distance of 1 m.

The values of the one meter intercept and the slope seems to be dependent on the weather condition. In general, the overall path loss increases as the sand storm becomes heavier. However, in the case of the very heavy storm, the measured slope of the path loss become smaller than in the case of a “regular” sand storm. This effect needs further investigation as it indicates that the relationship between the concentration of the sand in the air and the values for slope and intercept is not a simplistic one.
Figure 31: Average path loss as a function of log (d) for the four experiments

Table 14: Summary of the slope and intercept values for the four experimental environments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Slope m (dB/dec) (dB/dec)</th>
<th>One meter intercept PL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear sky</td>
<td>28.1</td>
<td>55.5</td>
</tr>
<tr>
<td>Dusty sky</td>
<td>32.4</td>
<td>53.3</td>
</tr>
<tr>
<td>Sand storm</td>
<td>36.1</td>
<td>54.4</td>
</tr>
<tr>
<td>Heavy sand storm</td>
<td>37.4</td>
<td>48.0</td>
</tr>
</tbody>
</table>
Figure 32: Average path loss and linear regression line for the 4 different weather

From the Table 14, the heavy storm has an m 3.7 value which is the many of sand particles made reflected waves from arriving signals, the dusty storm has 3.2 value because it has less obstructed sand and the normal sand storm has 3.6 value. The average of value is 3.5 in three different condition in sand and dust storm. The range collected data is listed in Table 15.

Table 15: Measurements collected at the transmitter side

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Range</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>22-59°C</td>
<td>2167</td>
</tr>
<tr>
<td>Pressure</td>
<td>983-974.89 mbar</td>
<td>2167</td>
</tr>
<tr>
<td>Humidity</td>
<td>13.2-92%</td>
<td>2167</td>
</tr>
<tr>
<td>Wind speed</td>
<td>3.2-82 mph</td>
<td>2167</td>
</tr>
</tbody>
</table>
Measurement versus predictions

Understanding and predicting the damage caused by sand and dust storm on wireless network sensors is an important issue [31]. The communication network can clearly understand the effect of the path loss propagation losses during sand storm. To understand the signal path losses among five sensors for distance up 5m-25m and the operating frequency is 2.4 GHz with the permittivity and conductivity of sand, defined in Table 16, will be used to illustrate the example, the antenna height of transmitter and receiver are assumed to be 0.1m.

**Table 16: Typical values of permittivity and conductivity for various sand types**

<table>
<thead>
<tr>
<th>Type of ground</th>
<th>σ(s)</th>
<th>ε_r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor ground</td>
<td>$10^{-3}$</td>
<td>4-7</td>
</tr>
<tr>
<td>Wet ground</td>
<td>$2*10^{-3}$</td>
<td>25-30</td>
</tr>
<tr>
<td>Sea water</td>
<td>5</td>
<td>81</td>
</tr>
<tr>
<td>High water</td>
<td>$10^{-2}$</td>
<td>81</td>
</tr>
<tr>
<td>Dry sand</td>
<td>3-6</td>
<td>0.15-0.2</td>
</tr>
<tr>
<td>Sand saturated</td>
<td>20-30</td>
<td>2-4</td>
</tr>
<tr>
<td>Sand stone</td>
<td>2-3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The experiments are defined on the basis of the sand storm severity. In the first experiment, the data are collected under a clear sky. This experiment is used as the baseline and it is referred to as E-1. The remaining three experiments are dusty sky (E-2), sand storm (E-3) and heavy sand storm (E-4) experiments. Tables 2 and 3 provide summary. Table 17 provides average path loss measurements, while Table
18 provides recorded environmental parameters associated with the four experiments. The path loss measurements are averaged across all eight radials. This is justified on the basis of the uniformity of the environment. In all experiments, the environment was very similar along each of the eight radial directions.

Table 17: The average of path loss a function of distance for four experimental environments

<table>
<thead>
<tr>
<th>TX-RX distance (m)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(d/1m)</td>
<td>0.70</td>
<td>1.00</td>
<td>1.18</td>
<td>1.30</td>
<td>1.40</td>
</tr>
<tr>
<td>E1 – clear sky</td>
<td>74.64</td>
<td>83.34</td>
<td>90.32</td>
<td>92.77</td>
<td>93.07</td>
</tr>
<tr>
<td>E2 – dusty sky</td>
<td>76.24</td>
<td>84.63</td>
<td>92.85</td>
<td>94.87</td>
<td>98.66</td>
</tr>
<tr>
<td>E3 – sand storm</td>
<td>80.97</td>
<td>87.33</td>
<td>97.85</td>
<td>102.02</td>
<td>104.89</td>
</tr>
<tr>
<td>E4 – heavy sand storm</td>
<td>85.87</td>
<td>88.79</td>
<td>99.21</td>
<td>103.83</td>
<td>108.29</td>
</tr>
</tbody>
</table>

The most important environmental parameter that impacts the propagation is the wind speed. It is provided in the last column of Table 18 in both km/h and m/s. The wind lifts the particles of dust and sand into the air. It is reasonable to expect that as the strength of the wind is increased, the density of the particles becomes higher and the impact on the propagation of the radio signals becomes more significant.
Table 18: Environmental parameters for four experimental environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Humidity (%)</th>
<th>Temperature (°C)</th>
<th>Pressure (mbar)</th>
<th>Wind speed (km/h, m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 – clear sky</td>
<td>19.1</td>
<td>34.7</td>
<td>1060</td>
<td>2.3, 0.6</td>
</tr>
<tr>
<td>E2 – dusty sky</td>
<td>27.8</td>
<td>45.7</td>
<td>974</td>
<td>13, 3.6</td>
</tr>
<tr>
<td>E3 – sand storm</td>
<td>31.6</td>
<td>34.7</td>
<td>959</td>
<td>13.6, 3.8</td>
</tr>
<tr>
<td>E4 – heavy sand storm</td>
<td>49.0</td>
<td>36.1</td>
<td>984</td>
<td>26.3, 7.3</td>
</tr>
</tbody>
</table>

**Proposed propagation model**

The signal propagation scenario under consideration in this work is illustrated in Fig. 33. The scenario is seen as the extension of the basic *two-ray* propagation over flat reflective surface [58]. However, unlike the basic two ray propagation, the scenario in Fig. 33 assumes that the space between the transmitter (TX) and the receiver (RX) contains a concentration of particles of dust or sand. These particles cause additional absorption of the energy of the radio signal and therefore, the propagation path loss is increased.
General form of the model equation

By following the same methodology as in [58] and taking into account the absorption from dust and sand, one obtains the path loss in the form given by:

\[
\text{PL}(d) = \frac{P_{TX}}{P_{RX}} = \left(\frac{4\pi d}{\lambda}\right)^2 \left|1 + \rho \exp(-j\Delta\phi)\right|^2 \frac{A(d)}{\text{Absorption due to sand}}
\]  

(14)

Where, \(\text{PL}(d)\) is the path loss between TX and RX that are separated by distance \(d\), \(P_{TX}\) is the transmit effective radiated power, \(P_{RX}\) is the received power, \(\lambda\) is the wavelength of the propagating wave, \(\rho\) is the complex value of the reflecting coefficient of the ground and \(\Delta\phi\) is the phase difference between the direct and
reflected waves at the RX antenna that is due to the difference in the length of their propagation paths.

The term \( A(d) \) represents the additional signal attenuation that is due to sand and dust absorption. Equation (14) assumes that both TX and RX antenna have unit gains.

From the geometry of the propagation scenario, presented in Fig. 33, one may easily obtain the value of the \( \Delta \phi \) as:

\[
\Delta \phi = \frac{\Delta d}{\lambda} \cdot 2\pi
\]  

(15)

Where

\[
\Delta d = d \left\{ \sqrt{1 + \left( \frac{h_{tx} + h_{rx}}{d^2} \right)^2} - \sqrt{1 + \left( \frac{h_{tx} - h_{rx}}{d^2} \right)^2} \right\}
\]  

(16)

In (16), quantities \( h_{tx} \) and \( h_{rx} \) represent the height of the transmitter and receiver antenna respectively. A significant factor in (14) is the reflection coefficient \( \rho \).

This factor depends on the properties of the ground and based on the ITU report published in [59], it may be determined using:
\[
\rho = \frac{\sin(\varphi) - \sqrt{C}}{\sin(\varphi) + \sqrt{C}}
\]  
(17)

Where \( \varphi \) is the grazing angle given by:

\[
\varphi = \tan^{-1}\left(\frac{h_{TX} + h_{RX}}{d}\right)
\]

And

for horizontal polarization

\[
C = \eta - \cos^2(\varphi)
\]  
(18)

for horizontal polarization

\[
C = \frac{(\eta - \cos^2(\varphi))}{\eta^2}
\]  
(19)

With

\[
\eta = \varepsilon_r(f) - j60\lambda\sigma(f)
\]  
(20)

Where

\[\varepsilon_r(f)\] relative permittivity of the ground surface at frequency \( f \)

\[\sigma(f)\] conductivity (S/m) of the surface at frequency \( f \)

As seen in (15)-(20), at a given frequency, the reflection coefficient is a function of geometry, wave polarization and properties of the ground. More specifically, the reflection coefficient depends on the relative permittivity and conductivity of the ground. For the environments considered in this report, the relative permittivity is
approximately 4.5 and the conductivity is 0.17 S/m, which are values typical for sand environments.

Term \( A(d) \) in (14) captures additional loss that is due to presence of dust and sand. The model assume that this term is in the form that satisfies:

\[
10 \log[A(d)] = 10\alpha \sqrt{\log \left( \frac{d}{\lambda} \right)}
\]  
(21)

Using (14) and (21), the path loss prediction of the model expressed in dB may be obtained as:

\[
\text{PL_{dB}}(d) = 10 \log \left( \frac{P_{RX}}{P_{TX}} \right) = 20 \log \left( \frac{4\pi d}{\lambda} \right) - 20 \log \left| 1 + \rho \exp(-j\Delta\phi) \right| + 10\alpha \sqrt{\log \left( \frac{d}{\lambda} \right)}
\]  
(22)

The model equation expressed in (22) has one parameter - \( \alpha \), that is a property of the propagation environment. This parameter captures the magnitude of the additional attenuation that is due to the presence of the sand. The value of the parameter may be obtained from measured data. Using measurements reported in Table 17, numerical values for the experimental setup shown in Table 19, and the process of linear regression, the values of the parameter \( \alpha \) for four different environments are obtained and reported in Table 20.
Table 19: Parameters of the experimental setup [60]

<table>
<thead>
<tr>
<th>Parameter of the experimental setup</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the TX antenna</td>
<td>$h_{TX}$</td>
<td>0.1</td>
<td>meter</td>
</tr>
<tr>
<td>Height of the RX antenna</td>
<td>$h_{RX}$</td>
<td>0.1</td>
<td>meter</td>
</tr>
<tr>
<td>Relative permittivity of the ground</td>
<td>$\varepsilon_r$</td>
<td>4.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Conductivity of the ground</td>
<td>$\sigma$</td>
<td>0.17</td>
<td>S/m</td>
</tr>
<tr>
<td>Frequency</td>
<td>$f$</td>
<td>2450</td>
<td>MHz</td>
</tr>
</tbody>
</table>

Table 20: Value of parameter $\alpha$ obtained through linear regression of the experimental data

<table>
<thead>
<tr>
<th>Environment</th>
<th>$\alpha$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 – clear sky</td>
<td>2.22</td>
</tr>
<tr>
<td>E2 – dusty sky</td>
<td>2.46</td>
</tr>
<tr>
<td>E3 – sand storm</td>
<td>2.95</td>
</tr>
<tr>
<td>E4 – heavy sand storm</td>
<td>3.21</td>
</tr>
</tbody>
</table>

**Relationship between $\alpha$ and wind speed**

It is reasonable to assume that the environmental parameter $\alpha$ in (22) is related to the concentration of the sand in the air. At the same time, the amount of the sand that is being lifted up during a sand storm is also related to the speed of the wind. Therefore, it is reasonable to expect that there is a dependence of $\alpha$ on the wind speed. For the data analyzed in this study, this dependence is illustrated in Fig. 34.
The figure also shows a regression line and an equation that may be used for prediction of $\alpha$ on the basis of the known wind speed given in m/s. In other words, if the wind speed in an area is available, the value of environmental parameter $\alpha$ may be determined using:

$$\alpha = 0.15v + 2.14 \quad (23)$$

Where $v$ represents the wind speed given in m/s.

Even though Fig. 34 shows the relationship between the wind speed and the environmental parameter $\alpha$, there seems to be a significant discrepancy at medium wind speeds. This may indicate that either there are other factors that need to be taken into account, or that a larger data set is needed for a statistically proper development of the model.

Figure 34: Relationship between parameter $\alpha$ and wind speed
Model Evaluation

The model described in (14)-(23) is tested on all the data collected during the four experiments. The results of the model prediction are shown in Fig. 35. Also, Table 21 characterizes the prediction error. To determine the mean and standard deviation of the error, all collected data from Tables 2, 4, 6 and 8 in [60] are used. As seen, there is a good agreement between the measurements and predictions. The average prediction error is close to zero with standard deviation of the error on the order of 3-4dB, except for experiment E-3. This may be considered adequate for network planning purposes, as it leads to reasonable fade margin values [61].

Figure 35: Comparison between the model predictions and measured data
Table 21: Evaluation of the prediction error

<table>
<thead>
<tr>
<th>Environment</th>
<th>Mean error (dB)</th>
<th>Standard deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 – clear sky</td>
<td>-0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>E2 – dusty sky</td>
<td>-2.2</td>
<td>7.1</td>
</tr>
<tr>
<td>E3 – sand storm</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td>E4 – heavy sand storm</td>
<td>-0.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Chapter 6: Summary and Future Work

Summary of Dissertation
This dissertation considers propagation path loss in wireless sensor networks that are deployed over the sandy terrain. The path loss is evaluated on the basis of empirical measurements. The sandy terrain is somewhat unique relative to other terrains. In the presence of wind, the sand particles are lifted in the air and the propagation environment for the radio signal changes. Based on the empirical data reported in this work, there is a measurable impact of the sand storms on the propagation path loss of the signal. In evaluated cases, the path loss seems to follow the log-distance path loss model with the slope and the reference distance intercept values that increase with the severity of the storm. The recorded one meter intercept values are in the range between 53 and 60dB, and the slope values are in the range between 28 and 37 dB/dec. This is in a good agreement with the path loss measurements previously reported in [4].

In addition, the dissertation presents an empirical model for WSN operating in sand storm environment. The model is based on data collected in 2.4GHz ISM band which is one of the most popular WSN bands. The model may be seen as a generalization of the two-ray propagation where a term is added to take into account the absorption of the radio wave that is due to presence of sand and dust particles. Furthermore, it is revealed that the wind speed is the most significant factor impacting the level of
the additional attenuation. Except in one of the conducted experiments, the mean of
the prediction error is smaller than 2.2dB, with standard deviation on the order 3-
4dB. Even in the worst case scenario the standard deviation of the prediction error
is on the order 7dB, which allows for a reasonable planning of the network.

**Future Work**

Future works should focus on physical modeling of the mechanism that cause
variability of the propagation of the path loss under various severities of the sand
storms. Based on the measurements reported in this study, the path loss increases
with the severity of the storm. This is a result in line with the expectations. However,
the observed relationships between the values of the slope and intercept and the storm
severity does not seem to be linear and warrants further investigation.

Some follow up to this work would be appropriate. First, there is an obvious need
for a more empirical thorough model verification. Also, the severity of the storm
may need additional characterization in terms of influencing factors. Based on the
findings in this paper, the wind speed seems to be significant, but not the only factor.
Finally, the form of the factor used by the model to capture additional losses due to
sand and dust was determined through trial and error. Some physical insight and
justification of this factor is highly desirable
References


Networks: a survey. *ACM Transactions on Sensor Networks (TOSN)*, 8(4), 34.


Appendix

XBee Arduino shield firmware

1- To get real temperature, pressure, humidity and wind speed. We code the
transmitter arduino shield as follow:

/*
Weather Shield Example
By: Nathan Seidle
SparkFun Electronics
Date: November 16th, 2013
License: This code is public domain but you buy me a beer if you use this and
we meet someday (Beerware license).
Much of this is based on Mike Grusin's USB Weather Board code:
https://www.sparkfun.com/products/10586
This code reads all the various sensors (wind speed, direction, rain gauge,
humidity, pressure, light, batt_lvl)
and reports it over the serial comm port. This can be easily routed to an datalogger
(such as OpenLog) or
a wireless transmitter (such as Electric Imp).
Measurements are reported once a second but windspeed and rain gauge are tied
to interrupts that are
calcualted at each report.
This example code assumes the GPS module is not used.
*/
#include <Wire.h> //I2C needed for sensors
#include "MPL3115A2.h" //Pressure sensor
#include "HTU21D.h" //Humidity sensor
MPL3115A2 myPressure; //Create an instance of the pressure sensor
HTU21D myHumidity; //Create an instance of the humidity sensor

int digitalpin = 10; //connect arduino pin 10 to xbee pin6
int rssi;
float time = 0; // timer

//Hardware pin definitions
//--=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-

// digital I/O pins
const byte WSPEED = 3;
const byte RAIN = 2;
const byte STAT1 = 7;
const byte STAT2 = 8;
// analog I/O pins
const byte REFERENCE_3V3 = A3;
const byte LIGHT = A1;
const byte BATT = A2;
const byte WDIR = A0;
//Global Variables
long lastSecond; //The millis counter to see when a second rolls by
byte seconds; //When it hits 60, increase the current minute
byte seconds_2m; //Keeps track of the "wind speed/dir avg" over last 2 minutes
byte minutes; //Keeps track of where we are in various arrays of data
byte minutes_10m; //Keeps track of where we are in wind gust/dir over last 10
minutes array of data
long lastWindCheck = 0;
volatile long lastWindIRQ = 0;
volatile byte windClicks = 0;
//We need to keep track of the following variables:
//Wind speed/dir each update (no storage)
//Wind gust/dir over the day (no storage)
//Wind speed/dir, avg over 2 minutes (store 1 per second)
//Wind gust/dir over last 10 minutes (store 1 per minute)
//Rain over the past hour (store 1 per minute)
//Total rain over date (store one per day)
byte windspdavg[120]; //120 bytes to keep track of 2 minute average
int winddiravg[120]; //120 ints to keep track of 2 minute average
float windgust_10m[10]; //10 floats to keep track of 10 minute max
int windgustdirection_10m[10]; //10 ints to keep track of 10 minute max
volatile float rainHour[60]; //60 floating numbers to keep track of 60 minutes of
rain
//These are all the weather values that wunderground expects:
int winddir = 0; // [0-360 instantaneous wind direction]
float windspeedmph = 0; // [mph instantaneous wind speed]
float windgustmph = 0; // [mph current wind gust, using software specific time
period]
int windgustdir = 0; // [0-360 using software specific time period]
float windspdmph_avg2m = 0; // [mph 2 minute average wind speed mph]
int winddir_avg2m = 0; // [0-360 2 minute average wind direction]
float windgustmph_10m = 0; // [mph past 10 minutes wind gust mph ]
int windgustdir_10m = 0; // [0-360 past 10 minutes wind gust direction]
float humidity = 0; // [%]
float tempf = 0; // [temperature F]
float rainin = 0; // [rain inches over the past hour] -- the accumulated rainfall in the past 60 min
volatile float dailyrainin = 0; // [rain inches so far today in local time]
//float baromin = 30.03;// [barom in] - It's hard to calculate baromin locally, do this in the agent
float pressure = 0;
//float dewptf; // [dewpoint F] - It's hard to calculate dewpoint locally, do this in the agent
float batt_lvl = 11.8; // [analog value from 0 to 1023]
float light_lvl = 455; // [analog value from 0 to 1023]
// volatiles are subject to modification by IRQs
volatile unsigned long raintime, rainlast, raininterval, rain;
//----------------------------------------------
//Interrupt routines (these are called by the hardware interrupts, not by the main code)
//----------------------------------------------
void rainIRQ()
// Count rain gauge bucket tips as they occur
// Activated by the magnet and reed switch in the rain gauge, attached to input D2
{
    raintime = millis(); // grab current time
    raininterval = raintime - rainlast; // calculate interval between this and last event
    if (raininterval > 10) // ignore switch-bounce glitches less than 10mS after initial edge
    {
        dailyrainin += 0.011; //Each dump is 0.011” of water
        rainHour[minutes] += 0.011; //Increase this minute's amount of rain
        rainlast = raintime; // set up for next event
    }
}
void wspeedIRQ()
// Activated by the magnet in the anemometer (2 ticks per rotation), attached to
// input D3
{
    if (millis() - lastWindIRQ > 10) // Ignore switch-bounce glitches less than 10ms
        (142MPH max reading) after the reed switch closes
    {
        lastWindIRQ = millis(); // Grab the current time
        windClicks++; // There is 1.492MPH for each click per second.
    }
}

void setup()
{
    Serial.begin(9600);
    Serial.println("Weather Shield Example");
    pinMode(A1, INPUT);
    pinMode(STAT1, OUTPUT); // Status LED Blue
    pinMode(STAT2, OUTPUT); // Status LED Green
    pinMode(WSPEED, INPUT_PULLUP); // input from wind meters windspeed
        sensor
    pinMode(RAIN, INPUT_PULLUP); // input from wind meters rain gauge sensor
    pinMode(REFERENCE_3V3, INPUT);
    pinMode(LIGHT, INPUT);
    // Configure the pressure sensor
    myPressure.begin(); // Get sensor online
    myPressure.setModeBarometer(); // Measure pressure in Pascals from 20 to 110 kPa
    myPressure.setOversampleRate(7); // Set Oversample to the recommended 128
    myPressure.enableEventFlags(); // Enable all three pressure and temp event flags
    // Configure the humidity sensor
    myHumidity.begin();
    seconds = 0;
    lastSecond = millis();
    // attach external interrupt pins to IRQ functions
    attachInterrupt(0, rainIRQ, FALLING);
    attachInterrupt(1, wspeedIRQ, FALLING);
    // turn on interrupts
    interrupts();
    Serial.println("Weather Shield online!");
}

void loop()
{
// Keep track of which minute it is
if(millis() - lastSecond >= 1000)
{
    digitalWrite(STAT1, HIGH); // Blink stat LED
    lastSecond += 1000;
    // Take a speed and direction reading every second for 2 minute average
    if(++seconds_2m > 119) seconds_2m = 0;
    // Calc the wind speed and direction every second for 120 second to get 2 minute average
    float currentSpeed = get_wind_speed();
    // float currentSpeed = random(5); // For testing
    int currentDirection = get_wind_direction();
    windspeedavg[seconds_2m] = (int)currentSpeed;
    winddiravg[seconds_2m] = currentDirection;
    // if(seconds_2m % 10 == 0) displayArrays(); // For testing
    // Check to see if this is a gust for the minute
    if(currentSpeed > windgust_10m[minutes_10m])
    {
        windgust_10m[minutes_10m] = currentSpeed;
        windgustdirection_10m[minutes_10m] = currentDirection;
    }
    // Check to see if this is a gust for the day
    if(currentSpeed > windgustmph)
    {
        windgustmph = currentSpeed;
        windgustdir = currentDirection;
    }
    if(++seconds > 59)
    {
        seconds = 0;
        if(++minutes > 59) minutes = 0;
        if(10m > 9) minutes_10m = 0;
        rainHour[minutes] = 0; // Zero out this minute's rainfall amount
        windgust_10m[minutes_10m] = 0; // Zero out this minute's gust
    }
    // Report all readings every second
    printWeather();
    digitalWrite(STAT1, LOW); // Turn off stat LED
}
delay(100);
void calcWeather()
{
    // Calc winddir
    winddir = get_wind_direction();
    // Calc windspeed
    windspeedmph = get_wind_speed();
    // Calc windgustmph
    // Calc windgustdir
    // Report the largest windgust today
    windgustmph = 0;
    windgustdir = 0;
    // Calc windspd_avg2m
    float temp = 0;
    for(int i = 0; i < 120; i++)
        temp += windspdavg[i];
    temp /= 120.0;
    windspd_avg2m = temp;
    // Calc winddir_avg2m
    temp = 0;  // Can't use winddir_avg2m because it's an int
    for(int i = 0; i < 120; i++)
        temp += winddiravg[i];
    temp /= 120;
    winddir_avg2m = temp;
    // Calc windgustmph_10m
    // Calc windgustdir_10m
    // Find the largest windgust in the last 10 minutes
    windgustmph_10m = 0;
    windgustdir_10m = 0;
    // Step through the 10 minutes
    for(int i = 0; i < 10; i++)
    {
        if(windgust_10m[i] > windgustmph_10m)
        {
            windgustmph_10m = windgust_10m[i];
            windgustdir_10m = windgustdirection_10m[i];
        }
    }
    // Calc humidity
    humidity = myHumidity.readHumidity();
    // float temp_h = myHumidity.readTemperature();
Serial.print(" TempH:");
Serial.print(temp_h, 2);
//Calc tempf from pressure sensor
tempf = myPressure.readTempF();
Serial.print(" TempP:");
Serial.print(tempf, 2);
//Total rainfall for the day is calculated within the interrupt
//Calculate amount of rainfall for the last 60 minutes
rainin = 0;
for(int i = 0 ; i < 60 ; i++)
rainin += rainHour[i];
//Calc pressure
pressure = myPressure.readPressure();
//Calc dewptf
//Calc light level
light_lvl = get_light_level();
//Calc battery level
batt_lvl = get_battery_level();
}
//This function returns the voltage of the light sensor based on the 3.3V rail
//This allows us to ignore what VCC might be (an Arduino plugged into USB has VCC of 4.5 to 5.2V)
float get_light_level()
{
float operatingVoltage = analogRead(REFERENCE_3V3);
float lightSensor = analogRead(LIGHT);
operatingVoltage = 3.3 / operatingVoltage; //The reference voltage is 3.3V
lightSensor = operatingVoltage * lightSensor;
return(lightSensor);
}
//This function returns the voltage of the raw pin based on the 3.3V rail
//This allows us to ignore what VCC might be (an Arduino plugged into USB has VCC of 4.5 to 5.2V)
//Battery level is connected to the RAW pin on Arduino and is fed through two 5% resistors:
//3.9K on the high side (R1), and 1K on the low side (R2)
float get_battery_level()
{
float operatingVoltage = analogRead(REFERENCE_3V3);
float rawVoltage = analogRead(BATT);
operatingVoltage = 3.30 / operatingVoltage; //The reference voltage is 3.3V
rawVoltage = operatingVoltage * rawVoltage; //Convert the 0 to 1023 int to actual voltage on BATT pin
rawVoltage *= 4.90; //(3.9k+1k)/1k - multiple BATT voltage by the voltage divider to get actual system voltage
return(rawVoltage);
}
//Returns the instataneous wind speed
float get_wind_speed()
{
  float deltaTime = millis() - lastWindCheck; //750ms
deltaTime /= 1000.0; //Covert to seconds
float windSpeed = (float)windClicks / deltaTime; //3 / 0.750s = 4
windClicks = 0; //Reset and start watching for new wind
lastWindCheck = millis();
windSpeed *= 1.492; //4 * 1.492 = 5.968MPH
/* Serial.println();
Serial.print("Windspeed:");
Serial.println(windSpeed);*/
return(windSpeed);
}
//Read the wind direction sensor, return heading in degrees
int get_wind_direction()
{
  unsigned int adc;
  adc = analogRead(WDIR); // get the current reading from the sensor
  // The following table is ADC readings for the wind direction sensor output, sorted from low to high.
  // Each threshold is the midpoint between adjacent headings. The output is degrees for that ADC reading.
  // Note that these are not in compass degree order! See Weather Meters datasheet for more information.
  if (adc < 380) return (113);
  if (adc < 393) return (68);
  if (adc < 414) return (90);
  if (adc < 456) return (158);
  if (adc < 508) return (135);
  if (adc < 551) return (203);
  if (adc < 615) return (180);
  if (adc < 680) return (23);
  if (adc < 746) return (45);
  if (adc < 801) return (248);
if (adc < 833) return (225);
if (adc < 878) return (338);
if (adc < 913) return (0);
if (adc < 940) return (293);
if (adc < 967) return (315);
if (adc < 990) return (270);
return (-1); // error, disconnected?
}

// Prints the various variables directly to the port
// I don't like the way this function is written but Arduino doesn't support floats under sprintf
void printWeather()
{
    calcWeather(); // Go calc all the various sensors
    rssi = pulseIn (digitalpin, LOW, 2500); // call function from arduino
    time = millis()/1000;
    Serial.print("1"),
    Serial.print(" ");
    Serial.print(time);
    Serial.print(" ");
    Serial.print(rssi);
    Serial.print(" ");
    Serial.print(humidity, 1);
    Serial.print(" ");
    Serial.print(tempf, 1);
    Serial.print(" ");
    Serial.print(pressure, 2);
    Serial.print(" ");
    // Serial.println();
    // delay(1000);

    float voltage=0;
    voltage=analogRead(A1);
    float wind=0;
    if (voltage<81)
    {
        wind=0;
    }
    else
    {
        voltage=voltage-81;
wind=(voltage*115.2)/328;
}
//Serial.print("The speed of wind is: ");
//Serial.print(wind);
//Serial.print(" Km/h / ");
Serial.print(wind/1.6);
Serial.println();
//Serial.println("M/h");

//delay(1000);
}

2- To get RSL we code the receiver with this code as follow:
void setup() {
  Serial.begin(9600);
  Serial.flush();
  delay(1000); // enter AT mode start
  Serial.print("+"); // AT
  Serial.print("+"); // AT
  Serial.print("+"); // AT
  Serial.flush();
  delay(1000); // enter AT mode finish
  while(Serial.available()>0){
    Serial.write(Serial.read());
  }
}

void loop(){
  Serial.println("ATDB");

  while(Serial.available()>0){
    Serial.write(Serial.read());
  }
  delay(750); // 3/4 a sec
}
function pl = g2ray(d,er,sigma,ht,hr,f)

    % two-ray model
    % pl = g2ray(d,er,sigma,ht,hr,f)
    %
    % f  - frequency in GHz
    % d  - distance between TX and RX in meters
    % er - relative permittivity
    % sigma - conductivity of the ground
    % ht - height of TX in meters
    % hr - height of the receiver in meters

    lambda = 3e8/(f*1e9);  % wavelength
    fi = atan((ht+hr)/d);  % grazing angle
    deltad = d*(sqrt((1+(ht+hr)^2)/d^2)-sqrt((1+(ht-hr)^2)/d^2));  % difference in distance traveled between two rays
    deltafi = deltad/lambda*2*pi;  % translate path distance into phase difference
    eta = er-sqrt(-1)*lambda*sigma;  % equations from ITU reports
    C = (eta-cos(fi)^2)/eta^2;
    Ro = (sin(fi)-sqrt(C))/(sin(fi)+sqrt(C));
    % reflection coefficient

    FSPL = -10*log10((lambda/(4*pi*d))^2);  % free space path loss
    REF = -10*log(abs(1+Ro*exp(-sqrt(-1)*deltafi))^2);  % loss due to superposition of two waves

    pl = FSPL+REF;  % total path loss