EFFECT OF CITRUS TREE CANOPY ON THE SIGNAL CHARACTERIESTICS OF A ZIGBEE-BASED MULTI-NODE WIRELESS NETWORK

By

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To my entire family & friends and to the loving memory of my mom

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Modern technologies in agriculture are a road to success. Currently wireless technology is the fastest growing technology and its advancement has many implications in agriculture and natural resources. Wireless sensor networks are progressively being implemented for environmental monitoring and agriculture to provide spatially accurate and continuous environmental information and real-time applications. Although the wireless instrument networks have many advantages and opportunities, they also have a number of technical challenges. So far wireless networking has been focused on high-speed and long range applications. However, there are many wireless monitoring and control applications for industrial and home environments which require longer battery life, lower data rates, and less complexity than those from existing standards. The placement of wireless nodes for wide area mesh coverage in an agricultural environment affects radio frequency propagation. Reliable communication is crucial for successful deployment of wireless sensor networks; therefore, it is important to understand the impact of crop canopies and environmental conditions on the performance of the radios used in the wireless network.

Given the need and desire to apply wireless sensor networks for agricultural applications; ZigBee-based, multi-node, wireless sensor networks were evaluated for their potential to act as

the data communication network within a citrus grove. For such wireless applications, a new standard called ZigBee has been developed by the ZigBee Alliance based upon the IEEE 802.15.4 standard. Signal strength was tested at various heights within the grove. It was observed that the strength of ZigBee radios was affected by the distance between the nodes and their height from the ground. The radio signals were also affected by the dew on the canopies and the relative humidity in the field. A simple composite model was developed to predict the signal strength of ZigBee radios within a grove environment which resulted in fairly accurate predictions. The experimental results not only provided a strong background on theoretical and experimental performance evaluation, but also gave an insight into the wireless performance in external agricultural environments such as citrus groves. The study signifies that the wireless technology can be readily adapted for various environmental monitoring projects such as remote management, control of farm operations, environmental control facilities; and technologies and networks that monitor pollutants of air and water.

CHAPTER 1
INTRODUCTION

Information in the form of data is a valuable resource to the farmers and it is important that this information is readily available to the farmer in order to efficiently utilize it. In the past few years, agricultural industry is experiencing a huge increase in the amount of information available for the farmers. This information can be collected, analyzed and used to manage inputs and outcomes in agricultural practices (Precision Agriculture in the 21st Century). New and better farm management opportunities are brought about by the development in positioning systems, sensor technologies, and computers. Spatial or geo-referenced data (information along with geographic data) has gained a lot of attention in the agricultural community.

The concept of relying on new technologies such as information technology to collect and analyze data in order to facilitate better management decisions is reflected in the concept of precision agriculture. Precision agriculture can be defined as a management strategy that uses information technologies to bring data from multiple sources to execute decisions associated with crop production. Improvements in microelectronics have made deployment of small, distributed, low power devices that integrate computing, sensing, and wireless communication within a field possible. The specific physical arrangement of the elements in the sensor network is known as the topology of the network. The wireless sensor network is a promising platform for in-field data collection in many agricultural applications. Cellular phones, radios, and Global Positioning Systems (GPS) have become essential tools, which have been used for communicating data. The amount of data required for decision-making is increasing nowadays as the process of capturing data is automated and facilitates frequent data capture. High speed telecommunications are limited in rural areas and it could be expensive to implement a permanent wired solution. The use of point-to-point wireless technologies and wide area wireless

networks can solve some of these communication barriers and also expedite the ability to send data to multiple locations at once.

Previously, sensor networks consisted of a small number of sensor nodes, which were wired to a central processing unit. Nowadays, the trend is more towards distributed and wireless sensing because when the exact location of a particular phenomenon is unknown, distributed sensing allows closer placement to the phenomenon than a single sensor. In addition, in many cases, multiple sensor nodes are required to overcome environmental obstacles like physical barriers, line-of-sight constraints, etc. The potential advantage of wireless transmission is the significant reduction and simplification in wiring. The wireless sensor networks permits faster deployment and installation of various types of sensors because many of these networks provide self-organizing, self-configuring, self-diagnosing, and self-healing capabilities to the sensor nodes. In spite of its advantages, the environment to be monitored does not have an existing infrastructure for neither energy nor communication. It becomes imperative for sensor nodes to survive on small, finite sources of energy, to communicate through a wireless communication channel.

Sensor networks can be used for a variety of applications. A few of them include environmental monitoring, which involves monitoring air, soil, and water, condition based maintenance; habitat monitoring, i.e. determining the plant and animal species population and behavior; precision agriculture applications such as data collection and reporting; and inventory tracking. In fact, due to the pervasive nature of micro-sensors, sensor networks have the potential to revolutionize the very way we understand and construct complex physical systems.

Environment Monitoring

Wireless sensors have been widely adopted in precision agriculture to aid in data collection for weather forecasts, spatial data, and precision irrigation. Environmental monitoring is one of

the applications where researchers would want to collect data from a set of points over a period of time, within an environment, in order to determine the trends and interdependencies. In this case, the researcher would want to get data from all the sensors periodically and later analyze the data offline. The goal would be to collect data over several months or years in order to observe the seasonal trends. For it to be meaningful, it would have to be collected at regular intervals.

At the network level, in this application, a large number of nodes would be continuously sensing and transmitting information back to the base station, storing all the information using conventional storage techniques. Generally, these nodes would be distributed in an outdoor environment requiring very low data rates and long lifetimes. It is not necessary that the nodes develop an optimal routing strategy on their own because the physical topology of the network would remain constant. Once the network is configured and setup, the nodes periodically sample the sensors and transmit the data back to the base station. Typically, the parameters measured are temperature, humidity, and light intensity which do not require a high frequency of reporting as they do not change quickly.

The most important characteristics in such applications are low data rates (data packets transmitted from the node per second), synchronization, long lifetime, and relatively static topologies. It is also not really essential to transfer all the data to the central collector in real time. The transmissions can be delayed as necessary to improve the efficiency of the network.

Habitat Monitoring

Habitat monitoring is yet another important application of wireless sensor networks. Recently, there has been concern on the potential impacts of human presence in monitoring animals and plants in their habitat. Anderson's (1995) research on mid coast Maine seabird colonies suggests that a 15 min visit to cormorant colony can result in 20% mortality among chicks and eggs in a given breeding year. Human disturbance may have an impact on the

behavioral pattern of plants and animals, and direct impact on the population of animals by increasing the stress and causing them to move to less suitable habitats. In the case of plants, they are also sensitive to trampling; and introduction of foreign machinery may disrupt their normal behavior. These effects are particularly common on small islands, where it is impossible to avoid human intervention for monitoring purposes. The islands serve as a shelter for a few species which cannot settle in with terrestrial mammals; for e.g. sea bird colonies are very sensitive to human disturbance.

Sensor networks thus represent an important advancement over the conventional invasive methods of monitoring. These sensors can be installed or deployed prior to the commencement of the breeding season or other sensitive seasons in case of animals and during dormancy in the case of botanical studies. These studies are highly useful and can be compared with the conventional methods of monitoring which involve human interference. The sensor networks are especially useful for long term studies. A strategy of deploying the sensors with occasional maintenance would avoid all the hassle involved in labor-intensive methods. The advantage of such methods is that there is access to a wide array of habitats which were previously challenging to monitor due to frequent visits to the site.

Precision Agriculture

Precision agriculture is a promising domain where wireless sensor networks could be exploited. Precision agriculture concentrates on providing means for assessing, observing, and controlling agricultural practices. Precision agriculture can be thought as a four phase cycle. The first being data collection and interpretation. It also comprises of the measurement of parameters characterizing the soil and crops. The data collection is automated to a certain extent whereas the data interpretation is not yet automated. The second phase is decision making, in which the farmer makes some management decisions as the data interpretation techniques are not yet

automated. The third phase is an implementation of a plan; such as the application of precision field operations. And the final phase is the evaluation phase, which involves variable rate seeding, and fertilizer and spray applications.

The potential of precision farming is that, more and better information to the producers can reduce uncertainties in decision making. For e.g., wireless sensor networks facilitates more detailed sampling techniques for in-field decision making. There are many systems that are available to monitor crop physiology and to improve the crop yield. Most of them are based on aerial and orbital platforms, which make them less adaptable for application specific or crop specific uses. In addition, for observation of an agricultural field with air-borne radars, even if the spatial resolution is adequate, the temporal resolutions are often limited due to the overpass frequency of the satellite and therefore, may be too coarse to capture short term phenology and rapidly changing localized meteorological conditions crucial for proper crop growth.

For monitoring small scale land such as agricultural plots, an autonomous ground-base sensor network could be more economical to implement compared to the aerial systems. It can also offer all weather, 24-hour, uninterrupted observational capabilities. In order to demonstrate the practicality of a ground-based sensor network, signal response and sensitivity to a vegetation layer must be examined in an accurate manner.

The presence of trees in the line-of-sight between transmitters and receivers cause attenuation. Foliage loss is an intricate topic where all variables and parameters have to be considered for predicting loss. Furthermore, the rising use of third generation (3G) radio interfaces such as International Mobile Telecommunications 2000 (IMT2000), require complicated radio planning techniques to accurately predict signal loss and efficiently use the existing frequency bands. Due to the differing range of applications, instruments must be able to

communicate with each other at different distances and in different environments. When operated in a habitat monitoring environment, they have to communicate with each other at very long distances. Therefore, the wireless instruments should be able to communicate with each other at a reasonable transmission range. Where extended range is required, additional nodes can be introduced into the network to route the data to the intended receiving node. However, there exists a trade off between the transmission range and battery life since a longer transmission range requires a higher transmission power. At the operating frequencies, attenuation caused by trees is considered as one of the major factors in radio propagation in both rural and suburban area. A few models exist to predict the attenuation loss through a vegetation medium, but the model presented in this study is developed for citrus orchard and under certain field and environmental conditions related to the experimental setup.

CHAPTER 2
BACKGROUND

Fundamentals of Radio Wave Propagation

Rapid advancement in technologies such as micro-electro-mechanical systems (MEMS), wireless communication and low power embedded processing have made wireless sensor networks (WSN) a reality. WSN consist of small on-board processing and communication units along with inexpensive sensing capabilities. Earlier, such devices were connected using wires, but now with the progress in routing algorithms, it is now possible for these devices to communicate through wireless links.

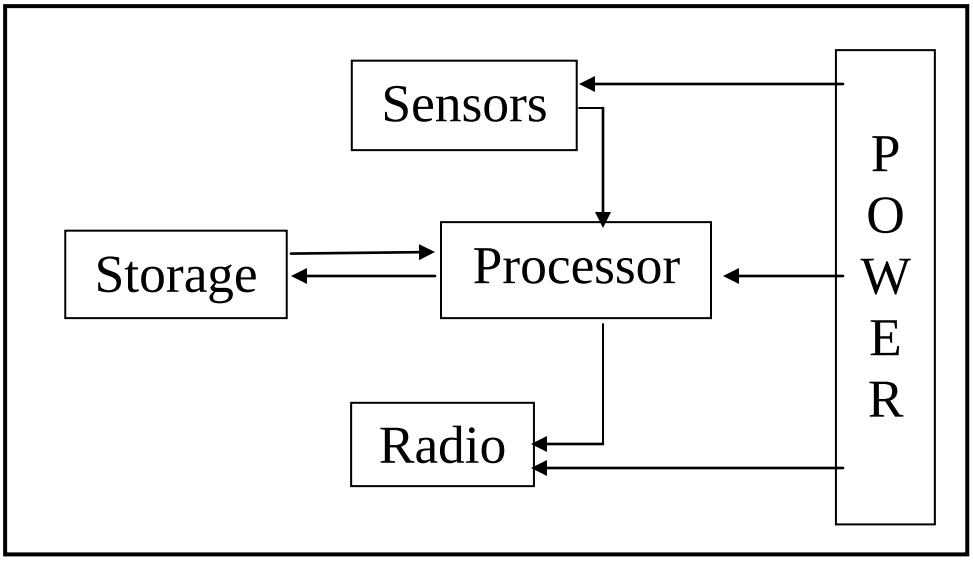

Figure 2-1. Wireless Sensor Schematic

Sensor networking is not a totally new concept to agriculture as various mechatronic research groups have implemented sensor networks in the harshest of operating conditions (Tian et al., 1999, Stone et al., 1999 and Darr, 2004). Each device connected to a sensor network is defined as a node and has two components, namely an embedded system component and transceiver component. The embedded system component includes the processor, voltage regulation, signal conditioning and peripheral devices. The transceiver component is a

combination of the transmitter and receiver module which uses an antenna for bi directional communication of electromagnetic waves (Perkins et al., 2002). Electromagnetic radiation is defined as the energy in the form of waves that self propagate in space. It has both the electric and magnetic components which oscillate perpendicular to each other and to the direction of propagation. The antenna is a component designed to send and receive electromagnetic radio waves by converting current into electromagnetic waves and vice versa (Radio wave propagation - ARROYO ROMERA, Daniel PÉREZ GARRIDO, Alonso).

The wireless devices use air, water or atmosphere as a medium whereas wired systems use metallic wire. In order for antennas to radiate electromagnetic waves a time varying current or acceleration of charge is required. The radiation pattern obtained from an antenna displays the performance of the antenna in-terms of radiation produced and highlights areas of poor performance. Any antenna that radiates equally in all directions is called an Isotropic antenna. In reality they don't exist but are used as a comparison base against real antennas.

The power gain of an antenna is given by the ratio of the antenna's radiation intensity to the radiation intensity of an isotropic antenna operating at the same power level. The antenna gain is generally calculated for an ideal isotropic source.

$$G\ (\theta, \emptyset) = ecd * \left(4\Pi\ *\ U * \frac{(\theta, \emptyset)}{Prad}\right) \qquad (1)$$

where, G (θ, Ø) is the gain at a given angular direction (no unit), e_{cd} is the antenna radiation efficiency (no unit), U (θ, Ø) is the radiation intensity at a given direction (dB) and P_{rad} is the total radiated power (dB).

The radiation density is difficult to measure in a natural environment due to disturbances caused by the surroundings. To determine the signal strength in an outdoor application the signal degradation can be quantified using any of the methods. Signal to Noise Ratio (SNR) and

Received Signal Strength Indicator (RSSI) are generally used to quantify signal loss. SNR measurement is given by the ratio of the desired signal power to the amount of background noise received corrupting the signal (Perkins et al., 2002). When the SNR is zero, the signal becomes ineffective for communication. Maximum SNR is desired for dependable communication. One method for improving SNR is by providing the source with high signal output power. RSSI is an indication of the amount of power is present in the received signal.

The environment in which the sensors are placed directly relates to the effectiveness of the network. All environments in which such networks are placed are subject to path loss and quantifying this loss attributed by different environment factors would be of great help for developing more effective network design and routing algorithms in the future. Clay (1998) suggested that a wireless mesh sensor network where nodes were spaced 30 to 100 m apart would offer full monitoring capabilities within a hectare of land. Ashley (1998) suggested a maximum of 10 to 20 dB loss above the least sensitive signal the transceiver can measure in order to have reliable communication between the communicating nodes.

In general, radio waves propagate directly from one point to another if a clear Line-of-Sight (LOS) exists. Depending on the environment, radio waves follow the surface of the earth and get absorbed or reflected in the environment in which they travel and manage to reach the other point when LOS does not exist. Everything the radio signal encounters in its way affects the signal by making it smaller or changing its direction. When modeling radio waves, small scale and large scale effects must be taken into consideration. The small scale effects are often those which are temporal or rather spatially concentrated, whereas large scale effects cover several hundred meters. Considering large scale effects, it is interesting to know how the signal reaches the receiver after traveling several hundreds or thousands of meters. In certain cases,

there exists no LOS between the transmitter and receiver. The radio waves depend on the propagation mechanisms mentioned below to communicate.

Baldassaro et al. (2002) were concerned with the prediction of signal strength for radio waves in the frequency range of 900 MHz and 28 GHz. Most of the models present then were too general and not of much practical use. It was observed that the models used for signal strength prediction were frequency independent and 2.4 GHz signals suffered less vegetative loss than the 28 GHz signals.

It is important to predict the path loss for short range communication devices as the loss can be considerable due to the following factors: absorption, reflection, refraction, scattering and diffraction. Free space propagation path loss is the widening out of the signal as it travels away from the antenna. The transmitting and receiving antenna are separated by a finite distance in free-space and have clear LOS. The environment is considered to have no obstacles and the gains of the antennas are ignored. The propagation loss is proportional to the distance and frequency. A part of the radio wave, energy is absorbed or reflected after being transmitted depending on the object it encounters in its path and the rest propagates and attenuates before it reaches the antenna. Attenuation is directly proportional to the frequency and distance. Absorption also depends on the material the RF wave encounters on its path and the absorption rate is also proportional to the frequency and the distance. Reflection may occur when a radio wave hits an object which cannot be penetrated. A part of the energy can be reflected and changes direction and the rest of the energy may reach the intended receiver. The amount of reflection is dependent on the grazing angle, i.e. the angle with which it hits the obstacle, and the reflective nature of the object (Radio wave propagation - ARROYO ROMERA, Daniel PÉREZ GARRIDO, Alonso). The wavelength of radio waves also determines the amount of reflection. The signal may take

multiple paths before it reaches the destination and a result may overlap with one another depending on the phase of the signal.

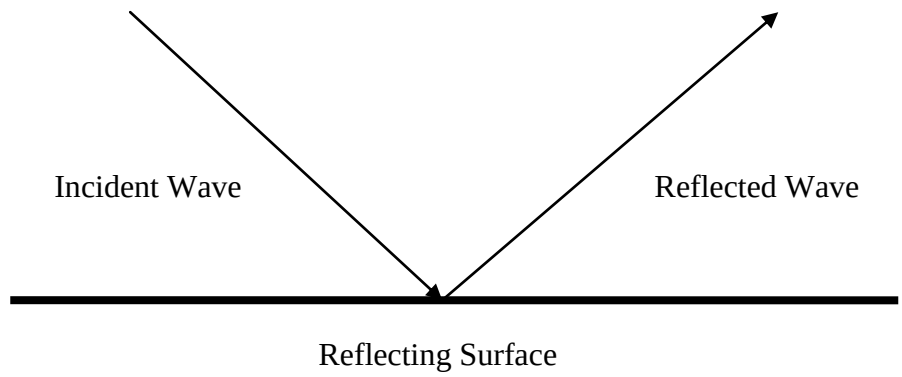

Figure 2-2. Wave reflection

Free Space Propagation Model

When radio waves hit a large number of objects having a dimension smaller compared to the wavelength itself, scattering occurs. Foliage and other small obstacles found in the environment are responsible for scattering.

Free space propagation model:

$$P_R(d) = \left(\frac{P_T * G_T * G_R * \lambda^2}{(4\Pi)^2 * d^2}\right) \quad (2)$$

Where, P_T is the transmitted power, $P_R(d)$ is the received power, G_T is the transmitter antenna gain, G_R is the receiver antenna gain, d is the distance between the transmitter and receiver (m), λ is the wavelength.

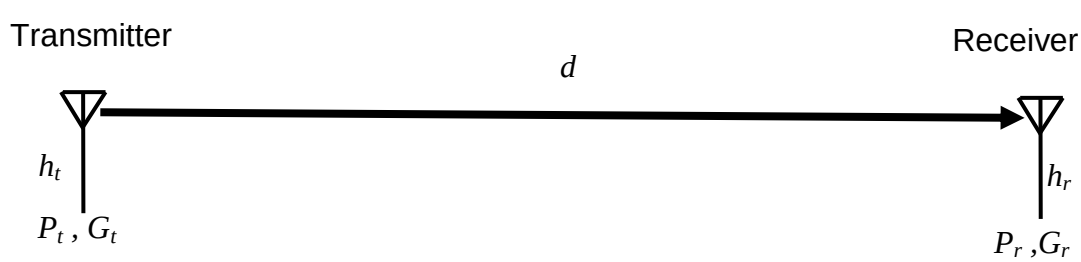

Figure 2-3. Free space propagation

The free space propagation model provides a lower bound for path loss and predicts the signal strength at the received end given by Friis free space equation. The model assumes that the transmitter and receiver have a clear LOS and the signal decays along with the distance between the transmitter and receiver.

Plane Earth Propagation Model

Reflection occurs when no direct LOS exists between the transmitter and receiver and in such cases the radio waves hit large surfaces and get reflected. Belloni (2004) determined the plane earth propagation model equation which accounts for interference caused by the reflected signal and the direct LOS signal.

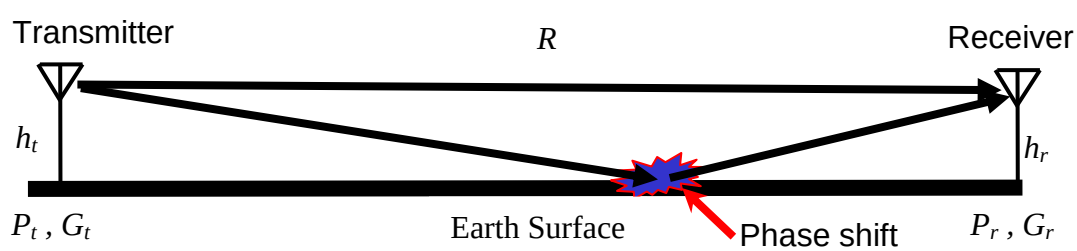

Figure 2-4. Plane earth propagation

The plane earth model tries to account for the interference caused by the reflected signal and the direct LOS.

Plane earth model:

$$P_r = \left(\frac{P_t * G_t * G_r * h_t^2 * h_r^2}{R^4}\right) \quad (3)$$

where, P_t is the transmitted power, P_r is the received power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, R is the distance between the transmitter and receiver (m), this the height of the transmitting antenna (m) and h_r is the height of the receiving antenna (m). The path-loss component is generally ignored when small scale effects are considered as the distance

between the transmitter and receiver is relatively small. Although, in such scenarios there is a direct LOS, the radio wave may be received multiple times as it is reflected several times. These individual signals after being reflected or diffracted are called multi-path waves. Depending on their phase, the direct and ground reflected wave when received at the receiver may interfere, thereby reducing signal strength.

Weissberger Model

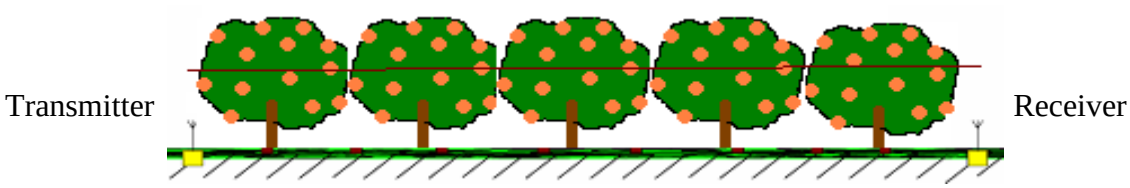

Figure 2-5. Weissberger model

The weissberger model is generally applicable for predicting path loss where the line of sight is blocked by dense trees. The loss is due to absorption of the waveform by the tree canopy. Weissberger model is given by

$$L_f = 1.33 * (f^{0.284}) * (d_f^{0.588}) \quad (4)$$

where, L_f is the foliage loss, f is the frequency of radio wave (GHz) and d_f is the depth of foliage along line of sight (m).

Zhang (2004) examined the propagation effects of the 2.4 GHz Bluetooth signal over corn, soy and bare field in Illinois. It was reported that with increase in antenna height, there was a decrease in the radio range, in particular in the soy bean field where there was a decrease in the radio range of 20 m for a 0.3 m increase in antenna height to 2 m. Patwari et al. (1999) examined the multi-path fading characteristics in peer-to-peer communicating systems at 1.8 GHz and reported a variance of 10 to 20 dB in signal strength. Goense et al. (2005) examined the propagation of Chipcon CC100 radio waves within a potato field. It was observed that the radio

waves propagated better in the presence of high humidity and the radio range was reduced by 10 m when the potato crop began flowering. Hebel et al. (2007) studied the effect of height and placement of nodes over a grassy field and reported a drop in signal strength between two 2.4 GHz radios on increasing the height from 1.5 to 2 m. They also observed a 5 dB loss in signal strength for a distance of 100 m between the two communicating radios at a height 1.5 m.

Seidel and Rappaport (1992) developed path loss models for predicting the wireless signal attenuation at 914 MHz in multi-floored buildings. This distant-dependant model was widely used to predict the signal attenuation. Andersen et al. (1995) developed similar path loss models for radio frequencies of 900 MHz, 1,300 MHz, 1,500 MHz, 1,900 MHz, and 4,000 MHz. Path loss models which considered LOS and NLOS transmission at 5 GHz within residential homes were developed by Ghassemzadeh et al. (2003). Lott and Forkel (2001) developed a multi-wall and floor path loss model at 5 GHz within commercial structures.

Most of the above research focuses on path loss within commercial structures; however, path loss models for the 2.4 GHz frequency that ZigBee operates at do not exist. Liechty et al. (2007) demonstrated an empirical path loss model, based on the Siedel Rappaport model, for 2.4GHz in an outdoor environment. Lymberopoulos et al. (2006) demonstrated the characteristics of radio signal strength variability using wireless ZigBee transceivers in an indoor environment. It was observed that antenna orientation greatly affected the signal transmission.

The performance of wireless transmission systems can be affected by many factors related to both the design of the sensor components and the environment in which it is placed. Much work has been done previously to analyze the performance of wireless systems within commercial office structures and around metropolitan areas, i.e. wireless networking for office lighting. All the above studies provide a strong foundation in theoretical and experimental

performance evaluation, but provide little insight into wireless performance in external environments such as citrus orchard. Wireless systems in general must communicate over inconsistent data channels. For example, multipath and interference is expected in a dynamic environment such as inside of an office or an industrial manufacturing space. Even in 'static' deployments for outdoor applications these networks are impacted by time-varying environmental conditions.

ZigBee is designed as a low-cost, low-power, low-data rate wireless mesh technology and has quickly become the global control/sensor network standard for many applications. It operates in the 2.4 GHz band and has data rates up to 250 Kbps. Considering the low power requirements and reliable delivery of data within a field, nodes that are ZigBee compliant would be of much use in agricultural applications. The ZigBee specification identifies three kinds of devices that incorporate ZigBee radios, with all three found in a typical ZigBee network:

- A coordinator, which organizes the network and maintains routing tables.
- Routers, which can talk to the coordinator, to other routers and to reduced-function end devices.
- Reduced-function end devices, which can talk to routers and the coordinator, but not to each other.

To minimize power consumption and promote long battery life in battery-powered devices, end devices can spend most of their time in "sleep" mode, or turning on only when they need to communicate. The ZigBee routers and coordinator do not go to sleep as they have to be aware of all the changes within the network.

Although the wireless instrument networks have many advantages and opportunities, they also have a number of technical challenges. Optimum wireless sensor network design and layout can only be achieved if all factors which affect wireless communication are documented. Given the need and desire to apply wireless sensor networks within these environments, work in this

area will generate new knowledge on the challenges and potential for wireless sensor network adoption.

Radio Frequency (RF) Coexistence

Some of the standardized wireless local area networks, e.g. ZigBee, WiFi and Bluetooth share the same 2.4 GHz industrial scientific and medical (ISM) unlicensed band. Since these protocols have been designed for different purposes, they can be set up to operate within the same geographical area communication are within the range of each other. This exposes the wireless instruments to interference from other sources, which can cause an increase in the error packet rates or even a total failure of the transmission. This indicates that wireless instrument networks should use the best data transmission methods or employ extensive interference reduction techniques in order to have a better coexistence with other ISM band network devices.

Energy Issues

Wireless operations of instruments give them portability since most instruments are battery powered. This enables the nodes to be geographically dispersed. After installation, the nodes need to be attended only when there is a fault or when the batteries need to be changed. Therefore, wireless instruments should be able manage energy resources wisely in order to extend the lifetime of the network.

They should use highly energy efficient protocols in order to prolong battery life and minimize energy wastage. In wireless instrument networks where sampling, processing, data transmission and actuation are intense, the trade-off between these tasks plays an important role in power usage efficiency. Balancing these parameters is one of the most important and challenging parts of the design of such networks.

Wireless Network Protocols and Their Applications

IEEE 802.11 was initially developed for use with personal computers as a replacement for a traditional Ethernet cable. This protocol has undergone several iterations, mainly to achieve higher data transfer rates and modify the operating frequency.

Currently, IEEE 802.11g is the industry standard for wireless hotspots and remote wireless internet access. High data transfer rates, in the range of 54 Mbps in the 2.4 GHz ISM band are sustainable with the IEEE 802.11 g protocol.

Wi-Fi and Worldwide Interoperability for Microwave Access (WiMAX)

WiMAX is another form of the expanding wireless Ethernet field. With a potential transmission range of 50 km and a maximum data rate of 70 Mbps, WiMAX offers many advantages when compared with alternative systems. Current U.S. adoption has focused on the 2.4 GHz spectrum as an ideal operating range, although lower frequencies are being considered due to their potential for increased transmission distances.

Wi-Fi and WiMAX have different quality of service mechanisms. WiMAX typically uses a mechanism based on setting up connections between the base station and the user device, wherein each connection is based on specific scheduling algorithms. This means that quality of service parameters can be guaranteed every time there is a data transfer. Wi-Fi actually has a mechanism similar to that of fixed Ethernet, where packets can be prioritized based on the application.

Boffety et al., 2006 with their TWISTER project incorporated one of the most innovative projects by deploying broadband networks by satellite in rural areas in Europe. Many farmers could benefit from the sophisticated solution, as they often required internet connection while working in the farms and fields. They also had the luxury of remote livestock monitoring with means of a Wi-Fi webcam.

Guo and Zhang (2002) used the IEEE 802.11 protocol to synchronize the operation of tractors running in close proximity to each other within an agricultural field. The system employed for synchronization operation was successful in transmitting data but exhibited high current draws, thus requiring a dedicated power source. A similar sort of device has been incorporated in an automated grazing system for bovines (Butler et al., 2006). The system records the position of the animal within a pasture using a Wi-Fi network. The system also employed alarms to herd grazing animals in a specific direction.

Bluetooth

IEEE 802.15.1 or Bluetooth is a wireless standard targeted for short range communication and low power consumption for portable personal devices like printers etc. This standard was specified in 2002. It provides a means to connect and exchange information between devices such as laptop computer, cellular telephones, and Personal Digital Assistants (PDAs). Current Bluetooth implementation also operates in the 2.4 GHz ISM band and supports a data transfer rate of 3 Mbps. Bluetooth, like 802.11 can be configured in an Ad Hoc network. It allows two devices which operate on bluetooth to directly communicate and transfer data without having to pass through a router or base station and allows the devices to create associations with one another whenever they are within transmission range. Multiple Bluetooth nodes can be configured into a small network known as a piconet. This is a Star network formed by one master and multiple slave units. The limitation of this network type is that each remote node must be within the transmission distance of the master. This makes it difficult to expand the network range beyond a tight perimeter area.

Although being a standard communication protocol and operating in the same frequency range, it differs from Wi-Fi in several aspects. Wi-Fi provides higher throughput and has a

longer communication range. Wi-Fi also requires expensive hardware to setup and leads to high power consumption.

Kim et al. (2006) demonstrated a more advanced system for irrigation monitoring using the Bluetooth protocol, which allowed for real time access to field conditions. The system employed a high gain patch antenna and delivered sensor network data up to 700 meters away with a radio power consumption of 65 mA. Each field node was instrumented with appropriate sensors to measure soil temperature, soil moisture and air temperature. A solar panel was used to power the sensors. A host computer which acted as a router within the network was used to collect data from all the individual field nodes. In addition, local weather station data was stored by the host computer to improve the irrigation schedule. A sensor platform for cattle monitoring was developed by Nagl et al. (2003). This included more specific health monitors like a pulse oximeter, as well as a point-to-point wireless link through a Bluetooth connection.

Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) technology has been used in a variety of applications such as food processing and safety, product identity preservation, and inventory management (Hamrita and Hoffacker, 2005, and Nichols, 2004). RFID is classified into two categories, namely passive and active systems. Passive systems are the tiniest form of wireless technology. These systems contain an embedded controller, an antenna and a small amount of non-volatile memory. The passive systems are generally embedded into bar codes and other identity preservation devices for less than $1 per unit. Passive tags do not rely on battery power so they must be interrogated by an RFID reader. The tags when exposed to a continuous RF signal get its power from the RF signal. This power is stored for a short duration as electrical energy and is used to power the controller and allow it to transmit its tag identification data. The passive tags have a very short range of transmission, with most commercial systems under 2

meters. The active RFID tags are different from the passive tags as they have an imbedded battery, which allows the tag to collect continuous sensor data. These tags have wide application in the food industry and have been successfully used to verify shipping conditions of a variety of perishable items. These active tags have a better transmission range but require more maintenance compared to the passive tags due to battery charging requirements. This also makes them more expensive on a per unit basis.

Nichols (2004) reported imbedding commercial RFID transponders within simulated coarse sediment particles could be used to track the movement of particles after runoff. The sediment particles after runoff event were located using a reader. The new location of the particles after runoff was measured and logged using a real time kinematics (RTK) GPS system for future analysis. Hamrita and Hoffacker (2005) experimented with a small wireless soil monitoring sensor by burying it under the soil surface. These smart sensors reported the soil temperature information through a 13.56 MHz passive RFID tag. The sensors also included an embedded Motorola 68HC11 microcontroller and an integrated circuit thermometer. It was observed that the results showed a high correlation between the RFID reported temperature and measurements obtained by a traditional thermocouple. The limitations were that it had a maximum transmission range of less than one meter.

ZigBee

ZigBee is an established set of specifications formulated under the relevant task force IEEE 802.15.4 and is the global standard of communication protocol for wireless personal area networking. The ZigBee alliance was formulated during the same time the IEEE 802.15.4 work group was formulated in 2004. They soon discovered that both camps were aiming at the same goal and later decided to join forces. Today the marketable name for this technology is ZigBee. The main goal of this technology is quite different from that of personal wireless area networks,

i.e. instead of offering high data rates for long distances with high QoS, they intended to work in the ISM band with very low power consumption and cost requirements, and intended to serve the industrial, medical and residential applications. Thus, the standardized set of solutions called 'Layers' make possible features like easy implementation, low cost, very low power consumption reliable data transfer, and adequate security features.

ZigBee operates on the three lower layers of the stack architecture. The Network and Application Support Layer permits growth of network without consuming much power and includes the user defined application profiles. The PHY layer accommodates high level of integration by using direct sequence to enable cheaper implementations.

The MAC layer permits the use of several topologies without introducing complexity and can handle a large number of devices. There are three different types of ZigBee devices that operate on these layers and they all have 64-bit IEEE addresses.The star, tree and mesh topologies are supported by the ZigBee network layer. In a star topology, the network is controlled by one single device called the ZigBee coordinator, which act as a router to other networks. It stores information about the network in the form of routing tables. The Full Function Device (FFD) is an intermediary router, transmitting data from other devices. It needs lesser memory when compared to the coordinator node and can operate in all topologies and can also act as a coordinator node.

The Reduced Function Device (RFD) is a device just capable of talking in the network. It does not have routing functionality and requires much less memory. The RFD only talks to the network coordinator. The RFD is cheaper and easier to implement than the FFD. The standard ZigBee feature is its low power consumption which is required for two major modes of operation -Tx/Rx and sleep. These devices spend most of their time sleeping and wake up only when they

need to communicate and then go back to sleep, thereby minimizing power consumption and promoting long battery life. They operate on the three license free bands: 2.4-2.4835 GHz, 868-870 MHz and 902-928 MHz. Maximum data rates allowed for each of these frequency bands are fixed as 250 kbps at 2.4 GHz, 40 kbps at 915 MHz, and 20 kbps at 868 MHz.

The harsh nature of agricultural environments especially within groves and orchards makes data acquisition extremely arduous. ZigBee is gaining wide acceptance and its characteristics make it an ideal fit for meeting the challenges in such harsh agricultural environments. Recent technological advancements in wireless mesh network systems (i.e. ZigBee) meet these challenges and open the door to agricultural applications limited only to ones imagination. Zigbee and its mesh networking predecessors have seen many recent applications since its initial release and development in 2004. The first commercial mesh network nodes (also known as motes) were produced and distributed by Dust Networks Inc, Berkeley,CA. SmartMesh sensors allow for continuous data collection without human intervention which cut labor associated costs and improved data quality. Sensor networking technologies such as SmartMesh have proven to improve the energy efficiency of buildings by providing environmental sensor data at locations previously unattainable. Data suggests that by using SmartMesh technology energy consumption in a data center reduces by hundreds of thousands of kilowatt-hours annually (Dust Networks Inc.)

Issues with Wireless Technology:

These are few of the issues that we would have to consider while dealing with wireless sensor networks:

Limited Computational Power

The power restrictions of sensor nodes are raised due to their small physical size and lack of wires. Since the absence of wires results in lack of a constant power supply, not many power

options exist. Sensor nodes are typically battery-driven. However, because a sensor network may contain hundreds to thousands of nodes, and because often, wireless sensor networks are deployed in remote or hostile environments, it is difficult to replace or recharge batteries. The power is used for various operations in each node, such as running the sensors, processing the information gathered and data communication. In order to reduce energy utilized, each sensor node should automatically transmit readings after a certain number of readings. This would be a preferred alternative to the base station broadcasting a signal to each node, in turn, to tell it when it can send its data. With the first solution, if sensor nodes are transmitting at the same time, then there will be a high number of collisions. However, as nodes in the design will be setup well within transmission range of each other, the probability of collision is very low. The alternative solution wastes energy as transmissions are doubled across the network (base station request plus a sensor node reply) and the sensor node has to stay awake listening for the request.

Node Configuration

The high number of sensor nodes deployed in the network precludes dependence on manual configuration. Design-time pre-configuration is also not suitable due to the environmental characteristics to which the sensor nodes must adapt. Sensor node failure through destruction or loss of power, sensor nodes dropping in and out of transmission range and the unintentional movement of sensor nodes from external elements such as wind or animals will all contribute to a dynamic network topology. Therefore, self-configuration and periodic self-organization of the network are both required to continue proper function.

Error Prone Wireless Medium

Since sensor networks can be deployed in different situations, the requirements of each different application may vary significantly. We must take into consideration that the wireless

medium can be greatly be affected by noisy environments, and thus the signal attenuates depending on the amount of noise.

Scalable and Flexible Architecture

The network should be scalable and flexible to the enlargement of the network's size. Supposing we use communication protocols, they must be designed in such a way that deploying more nodes in the network does not affect routing and clustering. Rather, the protocols must adapt to the new topology and behave as expected. In other words, the network must preserve its stability. Introducing more nodes into the network means that additional communication messages will be exchanged, so that these nodes are integrated into the existing network. This must be done in a way that a minimum number of messages need to be exchanged among the sensor nodes, and thus battery power is not wasted unreasonably.

Fault Tolerance and Adaptability

If a sensor node fails due to a technical problem or consumption of its battery, the rest of the network must continue to operate without a problem. The nodes must be able to communicate using alternative routes within the network. Researchers must design adaptable protocols so that new links are established in case of node failure or link congestion.

Networking of Sensors

Sensor networks are capable of sharing information about their local environment with nearby peers and further relaying this information to a central node where it can be processed and used to improve the performance of the network. The biggest problem in deploying a sensor network in such an environment is related to its size and complexity. Sensor networking is not a new concept in agriculture as several research groups have implemented such networks in the harshest of operating conditions and have proven that reliable sensor networks can be developed. Under typical circumstances, a wired sensor network can be very costly since factory

communication wiring can easily cost $5 to $10 per foot to install. A simple solution to this problem is to eliminate the wires by employing wireless data communications, where radio links replace the point-to-point wiring.

Each device which is connected to the sensor network is defined as a node. These nodes when active require two key workings, the first being that the component is an embedded system which encompasses all the devices and peripherals required for operation. Secondly, the component should be a transceiver which acts as a bridge between the communication medium and the embedded system. A transceiver is nothing but a combination of a transmitter and receiver module which allows for bi-directional communication.

When lower level nodes are required, it is common that the transceiver element be replaced with a transmitter only to reduce cost and power consumption. The final necessity is the communication medium itself. The communication medium in which nodes pass information can be through a wired connection, a wireless radio transmission, or through other means such as light transmission through fiber optic cables and infrared wireless transceivers.

Network Topologies

There are several types of wireless networks available on the market today. They include: point-to-point networks, point-to-multipoint networks and the newly emerging mesh networks. In a point-to-point network, each network node directly communicates to only one other node. Wireless point-to-point systems are often used in wireless “backbone” systems such as microwave relay communications, or as a replacement for a single communication cable. The biggest disadvantage of a point-to-point wireless system is that it is strictly a one-to-one connection. This means that there is no redundancy in such a network at all. If the RF link between two point-to-point radios is not robust enough, the communicated data can be lost.

Point-to-multipoint networks generally have a star topology that can provide either one-way or two-way communication. Examples of such a topology include cellular systems, WLAN, and satellite systems in which one satellite station communicates to multiple ground stations. Signals in point-to-multipoint networks converge at the central node, for example, a base station of a cellular system, an access point of a WLAN or a satellite space station in a satellite system. The reliability of the networks with such a topology depends on the quality of the RF link between the central node and each end node.

In many environments, it can be impossible to find a location for the central node from which it is able to provide robust communication links with all of the end nodes in the network. Usually, moving the central node to improve communication with one end node will often degrade communication with other end nodes. As in a point-to-multipoint network, most of the wireless sensor network with a mesh topology also has a single central node to collect information from all the end nodes. However, the mesh topology is different from the point-to-multipoint topology in that every end node also can communicate with one or more nearby end nodes within the network.

In a mesh network, not only can each end node transmit its own information, i.e. information collected from its own sensor, but also it can relay information generated from other nodes. Thus, it is possible for the messages generated from an end node to reach the central node via multiple hops that is going through multiple other end nodes to finally reach the central node. The path that a message takes to reach the central node is called a “route”. And there may be multiple routes in a mesh network which can relay a message to the central node. The basic difference from how both point-to-point and point-to-multipoint topologies work is that in both of these topologies all of the transmissions are strictly limited to one hop. In addition, a mesh

network is often designed in such a way that it allows a message to automatically use another route when the quality of the current route is degraded. Considering all these factors and environmental circumstances, the use of multi point technology would be much favorable for both the sensor nodes and controllers.

The advantages of having a multi point sensing system are quite obvious. The field size definitely has a major role to play. The number of sensing points in a particular environment is proportional to the field size, the reason being, supposing we had a 20-acres citrus orchard and we only use a single point sensing system for the entire field to decide whether or not to irrigate. A decision cannot be based on the sensor reading as they represent a very small portion of the grove. Considering the area of the grove, there is a good chance that the soil would not be uniform and there would be immense spatial soil texture variability across the field. It is also known that changes in soil texture across a field affect moisture availability, which in turn affects the crop stand. In addition, changes in soil texture and soil moisture can significantly impact soil temperature. Basing the irrigation controllers on a single sensing system would be highly misleading due to the above mentioned facts, which could in turn trigger the control system to turn on and waste water. The control decisions must be based on multi-point sensing which can provide a clear picture of the entire field and not just a particular location in the field. Thus, by knowing the ambient conditions throughout a field, growers can optimize the amount of water used by turning on the irrigation controllers at the required places.

CHAPTER 3
MATERIALS AND METHOD

The measurement system was comprised of ZigBee based XBee Pro transceiver (MaxStream) nodes, a notebook running the data collection macro, an USB driven XBee transceiver, and a controller board. Rechargeable 9V batteries were used to power up all the modules in the field. In order to evaluate the data and perform quantitative analysis, XBee Pro nodes were tested for signal strength under varying conditions of distance, installation height, and environmental conditions.

XBee Pro Transceiver Nodes

These RF modules are easy to use and require very low power for their operation. They operate in the 2.4 GHz range and comply with IEEE 802.15.4 standard. Other features of these nodes are:

- Unique node addressing scheme
- Allows retries for non-acknowledged packet transmissions in point-to-point addressing
- Supports both point-to-point and broadcast addressing mode
- 11 channels in the 2.4GHz band
- Sensitivity of receiver (-100 dBm)

Figure 3-1. XBee Pro-Node

The XBee pro nodes (figure 3-1) for use within the field were mounted on AppBee Mod boards and these boards were installed on wooden poles at appropriate heights from the ground within the grove. The XBee unit was responsible for transmission and acknowledgement of data packets, and operated on 9600 baud rate.

USB Interface

By default all Xbee devices had address 0. Using the USB interface, the Xbees were addressed from 1 through 6 using the X-CTU software. The software gave access to the default Xbee settings using the READ button. The modified settings and firmware were updated using the WRITE button. Every XBee node had a unique 16 bit address starting from address 0. Any device was capable of communicating with any other device, which formed the point to point network. The MY and DL setting in the X-CTU configuration software (figure 3-4) represented the 16 bit node's own address and destination address.

Supposing data was to be sent from node 1 to node 2, the configuration would be MY = 1 and DL = 2. By default the data packets which are delivered along with an acknowledgement to the sender and are checked for errors with a maximum of 3 retries. Point to multi point network also exists where in a particular XBee node broadcasts to all the other nodes in the network.

This configuration is achieved by setting the DL to FFFF and sending the packet. This setup is useful when you want to poll all the nodes in the network or send a control message within the network. The network employed for the experiment was a fast polling one where in a BASIC Stamp coordinator was used to poll the devices. All the end nodes which were deployed in the field were assigned addresses from 1 through 6 and all of them had a destination address of 0 (DL = 0). All the end devices were polled in a round robin fashion to determine their RSSI values.

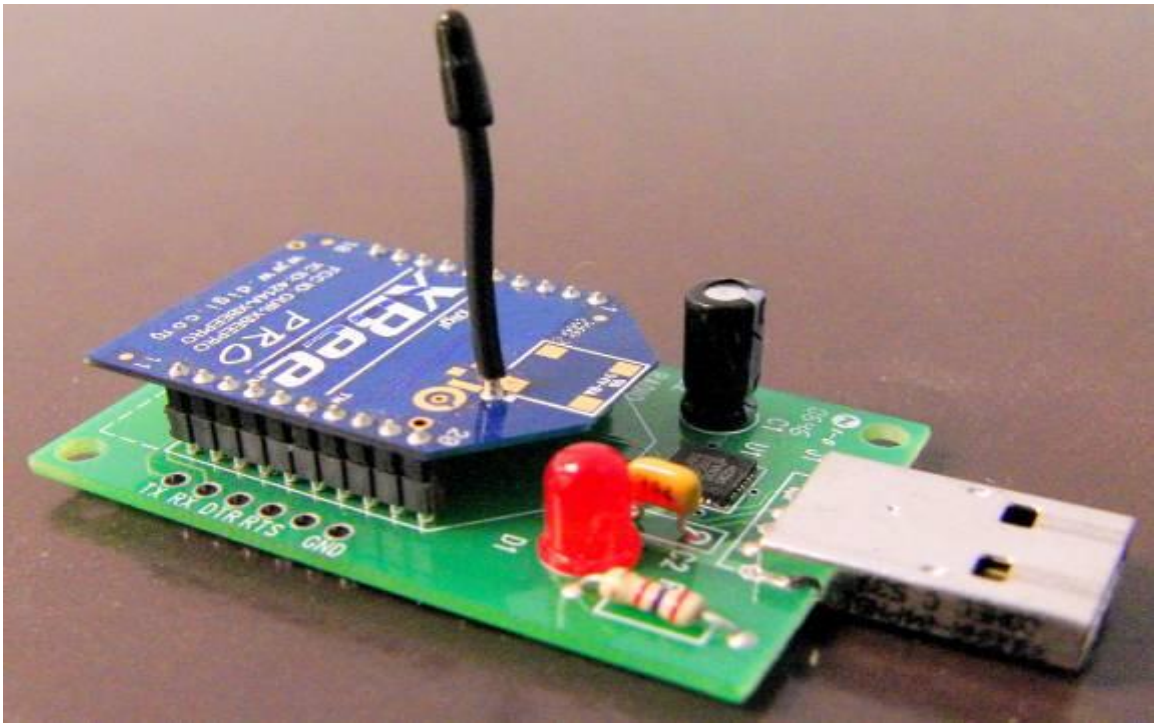

Figure 3-2. USB interface for XBee

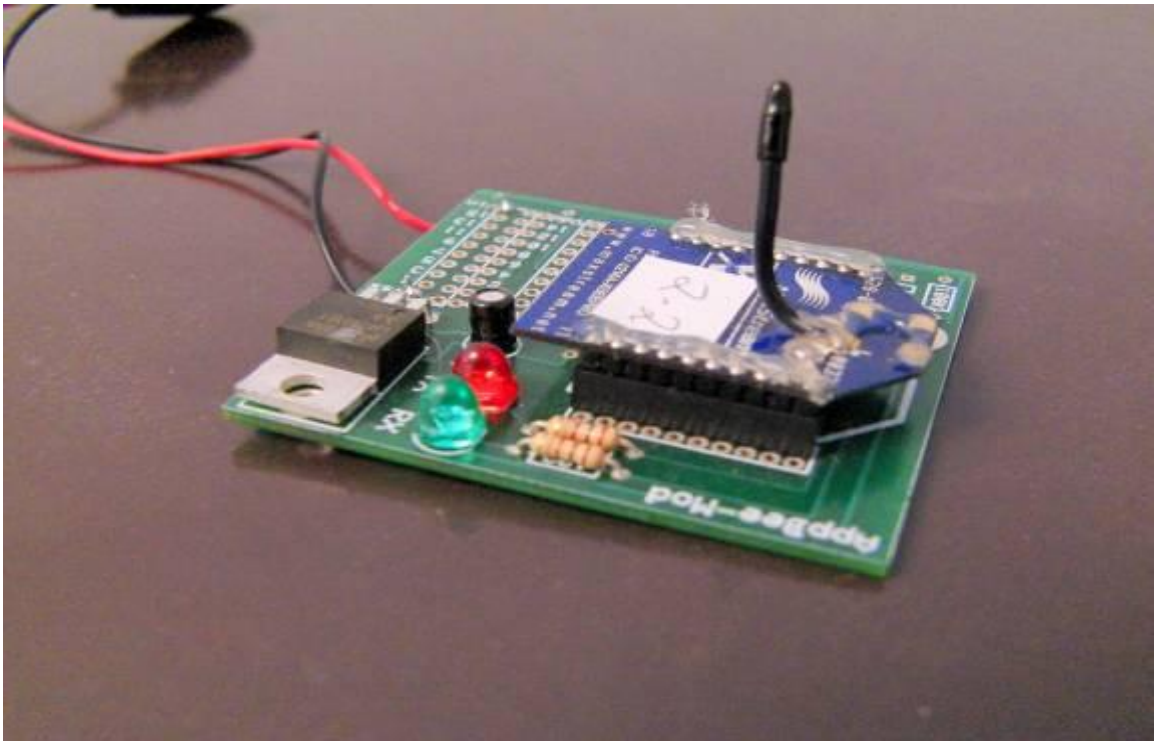

Figure 3-3. Xbee mounted on AppBee-MOD board

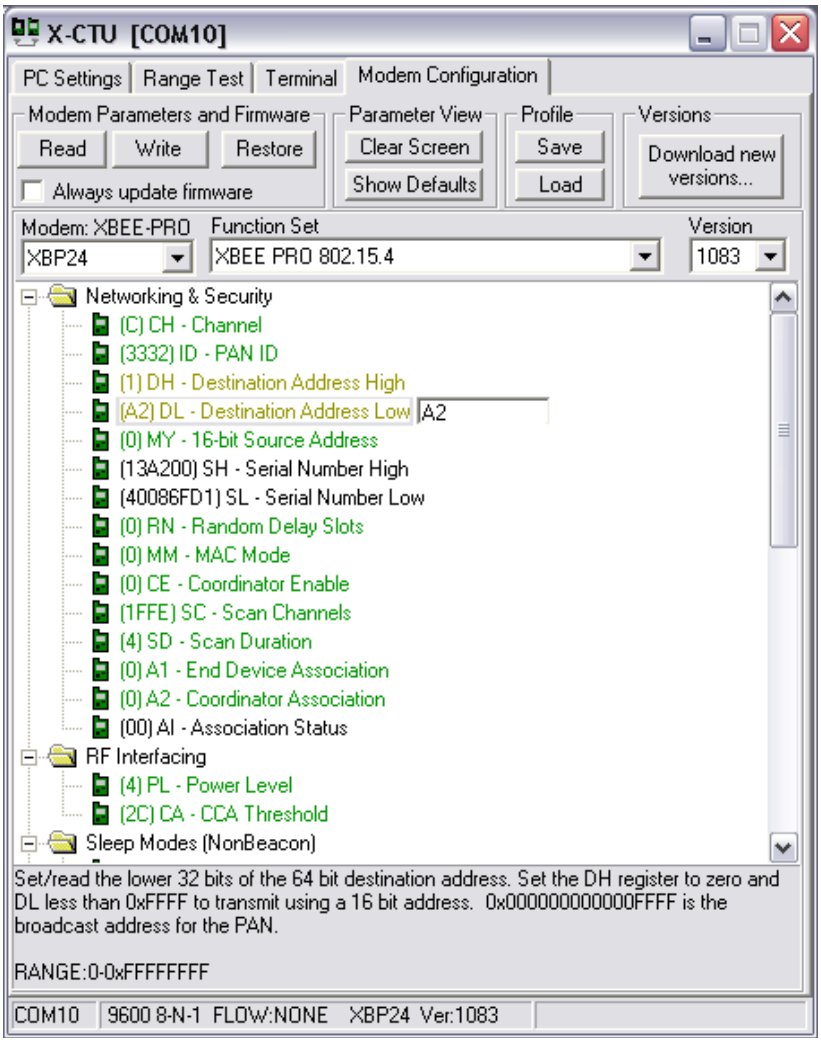

Figure 3-4. XCTU software modem configuration

Data Collection Macro

Stamp DAQ written in Visual Basic was used to perform transmission of packets, transmission retries, and Receiver Signal Strength Indication (RSSI) requests. The data were logged to an Excel file for analysis.

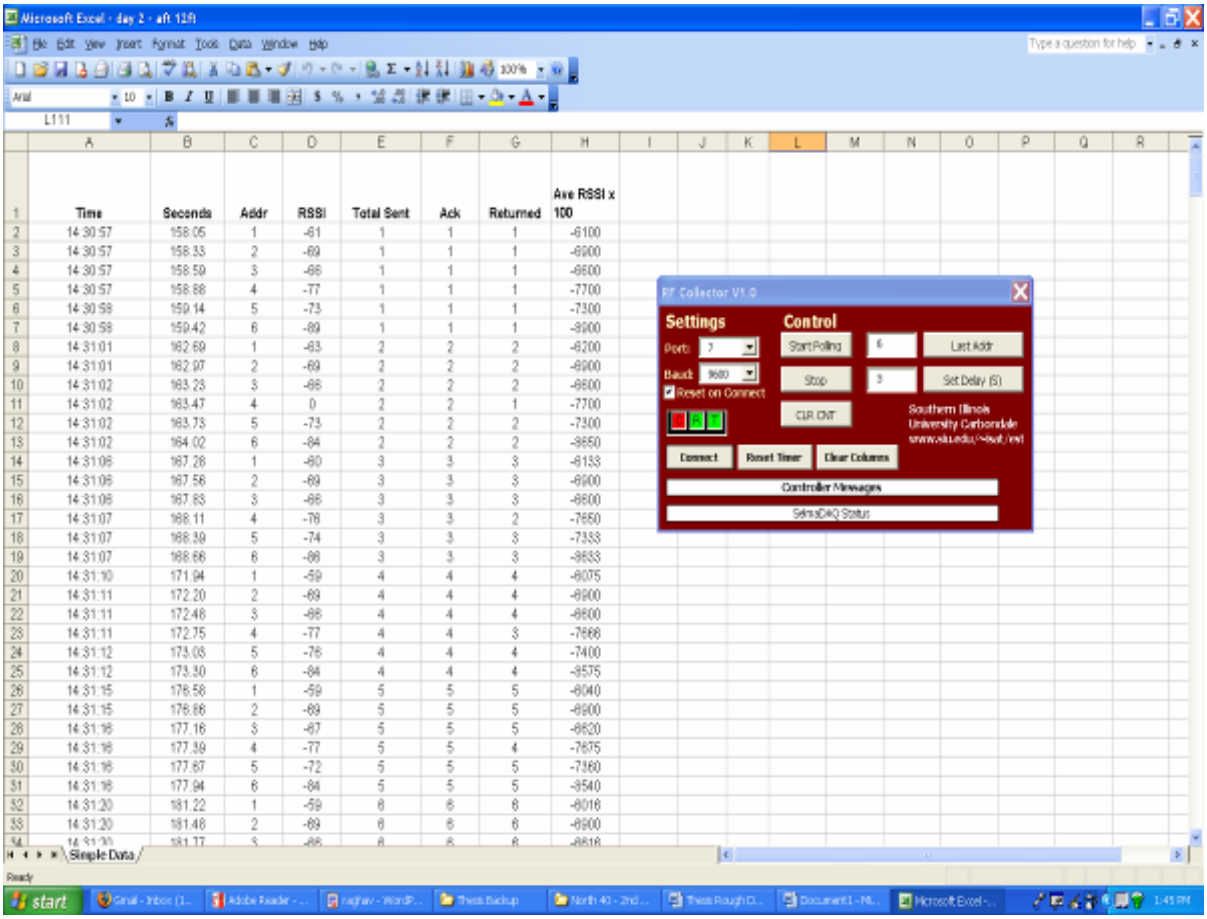

Figure 3-5. StampDAQ

Experimental Design

The variables used were classified as dependant and independent variables. Since, we were primarily interested in the dependant variable, which was the signal response; a factorial design approach was employed. In doing so, the effect of the independent variables and their interaction could be examined simultaneously. The dependant and independent variables are listed in Table 3-1.

Table 3-1. Independent and dependent variables

No.	Name	Type
1	RSSI	Dependent
2	Distance	Independent
3	Height	Independent
4	Direction	Independent

Description of Model Development

Modeling microwave propagation (i.e. the wavelengths are in the centimeter range) within a vegetation medium is a complex task. Sarabandi et al. (1987) modeled a leaf in a canopy as a single layer of resistive sheet and their stalks were modeled as long cylinders. The vegetation canopy was considered as scatterers and their scattering properties were governed by the orientation, size, shape, and dielectric properties. Modeling the canopy as a series of resistive sheets (scatterers) superimposed on each other is computationally very expensive.

Ulaby (1981) and Hornbuckle (2003) determined that plants were primarily made of water and 4% to 5% accounted for the dry vegetation in the canopy and about 95% of the canopy volume is occupied by air. It was also noted that the Dielectric constant (DC) of water was much greater than the DC of dry matter and thus, the plants DC is governed by its water content. Since the DC of air is smaller compared to that of water, one can say that the water content in the vegetation is responsible for radio absorption and scattering in the canopy.

Several methods for predicting the excess signal attenuation of millimeter wave signals when propagated through vegetation exist but they are either completely deterministic or empirical in nature. The present ITU-R recommendation is an empirical model developed from an earlier recommended ITU-R model where attenuation is calculated in terms of vegetation depth and frequency of the radio wave.

$$A = 0.2 * (f^{0.3}) * (d^{0.6}) \tag{5}$$

where, A is the attenuation (dB), f is the frequency used (GHz) and d is the vegetation depth (m). An improvement to this model was developed by researchers at Rutherford Appleton Laboratory based on a series of measurements and testing of the empirical vegetation attenuation models.

$$A = 15.6 * (f^{-0.009}) * (d^{0.26}) \quad (6)$$

It was observed that the new model had a better prediction of signal attenuation over the other existing empirical attenuation models. Seville (1997) observed that the variability of attenuation through the vegetation was significant and was a result of the random position of leaves and branches.

Monopole antennas were employed for the XBee pro nodes in the field and hence, radio propagation occurred in all directions resulting in path loss. The loss of radio signal due to environmental factors and distance was considered as path loss. Specifically, the distance between the nodes, and the effect of vegetation and soil were considered. This work provides a composite mathematical model, which combines the optimized vegetation attenuation model along with plane earth propagation loss model. Summing these losses together represents a model which corresponds to the short range path loss within the citrus grove, where the nodes were placed for measurement. The theory behind predicting received signal strength is to first determine the total path loss and subtract the path loss from the transmitted power. Hence the received signal strength was predicted by subtracting the total path loss from the transmitter power. From (3)

$$P_R = P_T * G_T * G_R (h_t * h_r / R^2)^2 \quad (7)$$

$$P_R / P_T = G_T * G_R (h_t * h_r / R^2)^2 \quad (8)$$

Path loss is the difference between the transmitted power and the received power at the antenna. Path loss is deduced as the transmitted power divided received power.

$$P_L = 10*\log P_T/P_R \quad (9)$$

$$P_L = 10*\log P_T/P_R = -10*\log G_T - 10\log*G_R - 20*\log h_t - 20*\log h_r + 40*\log R \quad (10)$$

The above equation represents the path loss experienced by the radio wave due to reflection of the earth. The path loss experienced by the radio wave due to canopy absorption is given by equation 6. Thus, by adding the two individual path losses, the total path loss experienced by the radio wave is obtained and is given by the following equation

$$Total\ Path\ Loss\ (dB) = 40\log*R - 10*\log G_T - 10\log*G_R - 20*\log h_t - 20*\log h_r + 15.6 * (f^{-0.009}) * (d^{0.26}) \quad (11)$$

Where, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, R is the distance between the transmitter and receiver (m), h_t is the height of the transmitting antenna (m), h_r is the height of the receiving antenna (m), f is the frequency used (GHz), d is the vegetation depth (m).

The total path loss was subtracted from the transmitter power to predict the signal strength at the receiver node. The path loss is a positive quantity and the received signal strength (P_R) is predicted using

$$P_R = P_T - P_L \quad (12)$$

where, P_T is the transmitter power (dBm) and P_L is the total path loss (dB)

Field Test

To validate the analytical predictions, tests were performed under a dense citrus grove at the Citrus Research and Education Center at Lake Alfred, FL which provided uniform foliage height (canopy) and minimized the effect of wind on signal propagation. The canopies had heights in the range of 3.25 - 3.5 m. Antenna heights of 0.5 m, 2 m and 3.5 m were tested at distances of 45 m, 60 m and 75 m to provide a study on the effect of distance, antenna height, and citrus canopy on signal strength.

Initial tests were conducted to find out the maximum range of the XBee Pro nodes within a citrus environment. Nodes were placed at distances of 75 m, 90 m, and 105 m, and it was observed that none of the packets reached the nodes placed at 90 m and 105 m. Packets received at the 75 m node had the least sensitivity of -101 dBm. The node was placed a little further than the 75 m marking and packet reception was observed. No packets were received on this new position. This meant that the maximum range for the XBee nodes within a citrus orchard with huge canopies was 75 m. During testing, random locations were chosen to run the test in the orchard. Three XBee Pro nodes were placed at distances 45, 60 and 75 m both along and across the row. The layout of the nodes within the field is shown in figure 3-7. The antenna height was randomized and batteries were replaced after each run to minimize the possible effects of battery power loss. A laptop running the data collection macro was tied to an XBee Pro transceiver with an address of FF called as the base. The node setup is shown in figure 3-6.

The base unit sent out a unique data packet through the controller board in the field having address 0, and continuously polled the various remote units and collected the received data and sent the results to the base. All the remote units and the controller board were placed on wooden poles with appropriate height markings and all the units were at the same level at any point in time. Each field unit required a unique address between 1 and 199 in hex. The collection unit sent a string out to the remote unit by its address; the string used was ABCDEFGHIJKLMNOPQRSTUVWXYZ0123456789. The following parameters were recorded: the RSSI level of returned data, the total number of packets sent, and the average RSSI (x 100). One hundred packets were transmitted for each distance-height point and for every 10 samples; the collection macro requested the RSSI level of the received packet. The remote units were configured for point-to-point addressing in order to ensure that the packets reached the base

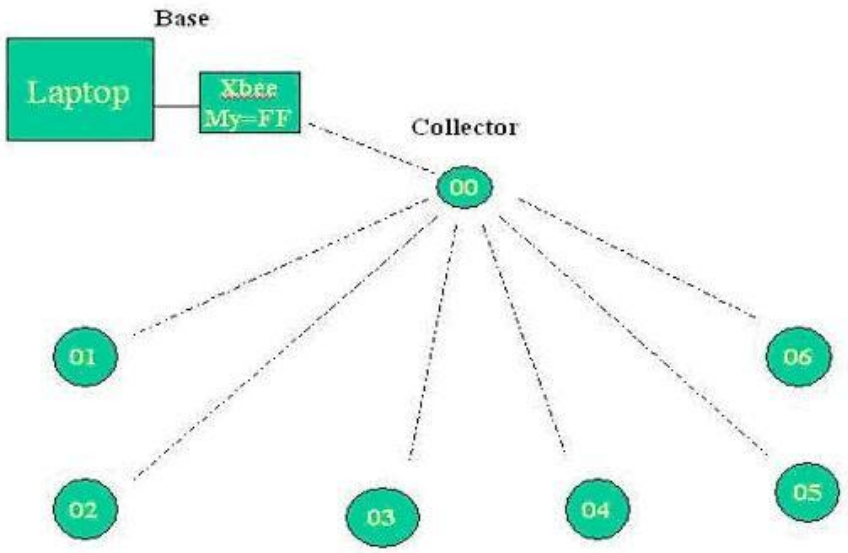

Figure 3-6. Node Setup

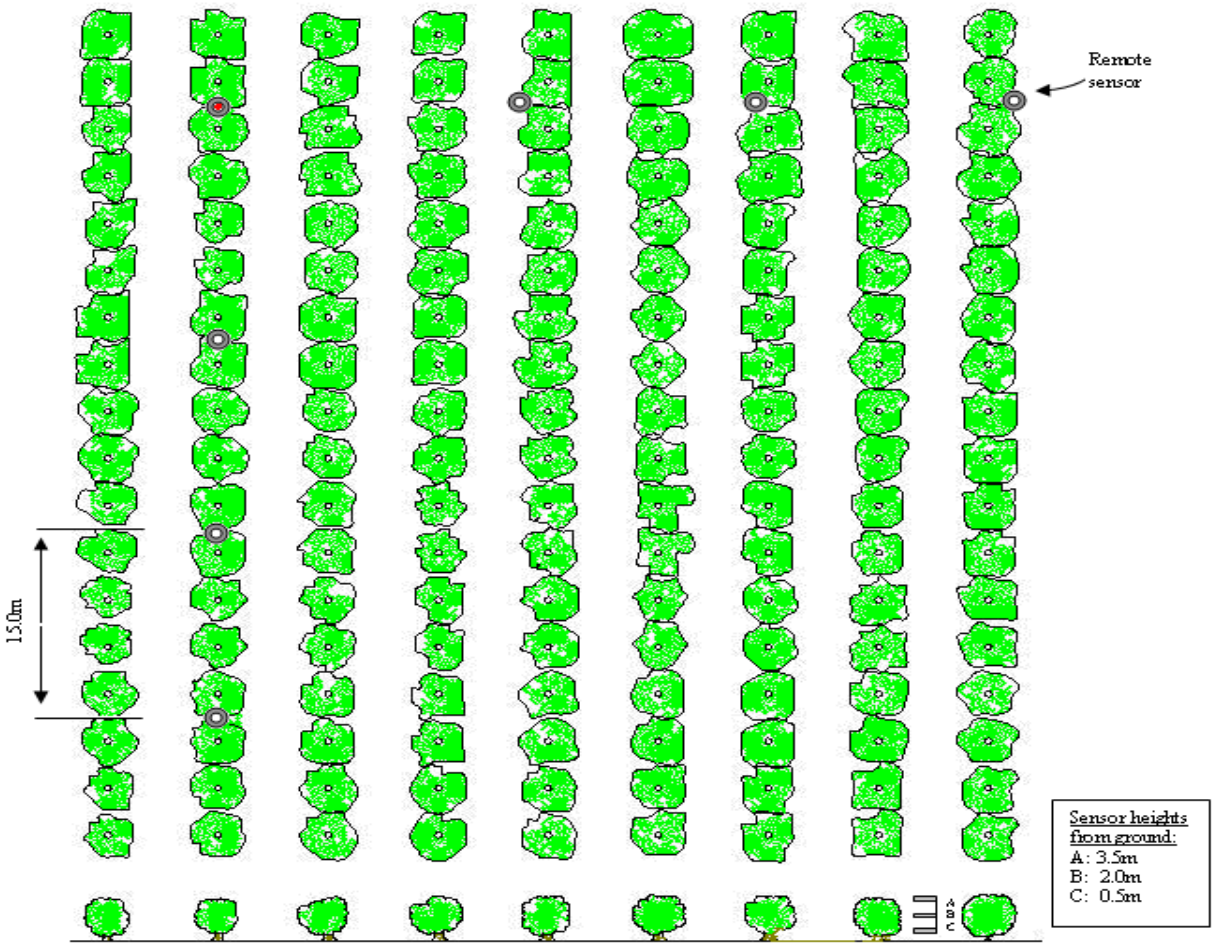

Figure 3-7. Field layout

with a higher probability. The base unit was configured for broadcasting mode so that the unit did not request for retries on not receiving any acknowledgements for the previous packets. The radio polarization was in the parallel direction to ensure the strongest signal strength.

In order to extend and obtain more useful information from this study, weather information was acquired at the time of experiment to analyze the effects of temperature and relative humidity on signal strength. The weather information was obtained from the Florida Automated Weather Network station at Lake Alfred on all days the experiment was performed.

The relative humidity and temperature data were extracted based on the time of the experiment. The RSSI data was grouped according to the three different heights and averaged across each day as morning and afternoon data. The average of the relative humidity and temperature were also calculated for each of that duration, and was combined with the RSSI data. This data was sorted based on relative humidity and temperature to determine if there existed any trend with increase or decrease in RSSI value for a corresponding decrease or increase in the relative humidity values. Similarly the temperature data was compared against the RSSI values.

CHAPTER 4
EXPERIMENTAL RESULTS

Effect of Distance-Height on Received Signal Strength Indicator (RSSI) Level

The data collected on the Excel file contained the address of the XBee Pro node for which the time and RSSI were recorded. It also contained the number of packets sent to each node and the number of acknowledgements each node sent out on reception of a packet.

RSSI data from the open ground test was used as a reference to compare the quality of transmission in the canopy environment for each node. Although tree height and density may not be directly related, the data gave a good idea on the performance of the sensor as the density of trees increased. Further, replications were performed under each condition to obtain accurate results.

The mean RSSI levels for each node were calculated by averaging the replications. The data were observed and reported for any trends and abnormalities. Further, analysis of variance was performed on the mean RSSI level to determine any significant interaction effects between any of the factors described in Table 3-1.

The field setup was used to perform a series of measurements which lasted nine days. Tests were performed to determine the signal strength levels over a range of height and distances. The experiment was repeated two times within a day, one in the early morning to account for the effects of morning dew on signal strength and one in the afternoon under normal conditions. SAS was used for all statistical analysis. ANOVA was conducted on all the calculated values and its results were interpreted at the significance level, alpha = 0.05.

From Table 4-1 it was observed that the mean of the RSSI was affected by

- Direction of placement of the nodes, i.e. along and across the rows
- Distance between the nodes along and across the rows.
- Height of the nodes from the ground

Figure 4-1 shows the average RSSI with respect to the distance for the experiments conducted during the morning at 2 m height. The data indicates the expected trend of decrease in signal strength with an increase in distance, due to signal absorption by canopies.

Table 4-1. ANOVA table for mean values of distribution

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Direction	1	50205956.5	50205956.5	13.24	0.0004
Height	2	53836769.5	26918384.7	7.10	0.0011
Distance	2	43904887.4	21952443.7	5.79	0.0036
Direction*Height	2	50105720.4	25052860.2	6.61	0.0017
Direction*Distance	2	118835971.8	59417985.9	15.67	<.0001
Height*Distance	4	77139428.5	19284857.1	5.09	0.0007
Direction*Height*Distance	4	100149146.1	25037286.5	6.60	<.0001

The data from all the 9 days was averaged based on the repetitions to form three different sets as day1, day 2 and day 3.

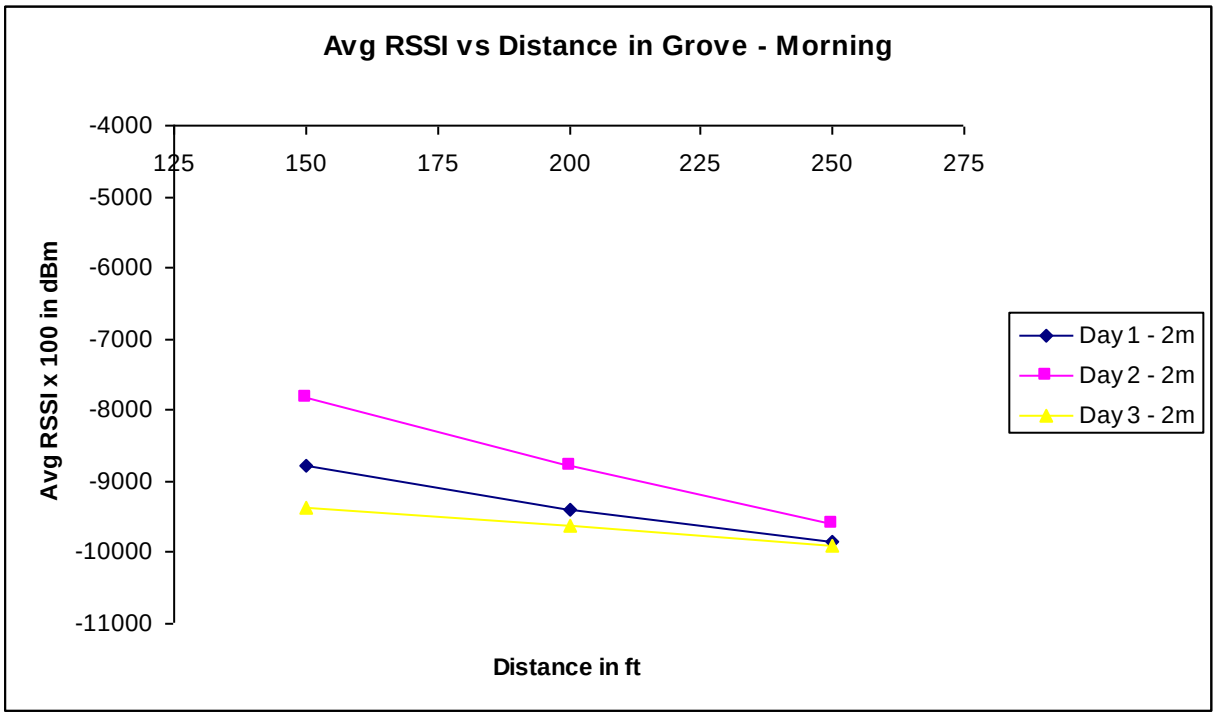

Figure 4-1. Average RSSI vs. distance in grove at 2 m height – Morning

Figure 4-2 shows the results of the same experiment conducted during the afternoon under normal conditions. The nodes appear to have better signal strength in the afternoon than in the

morning. There was no difference in the setup between morning and afternoon; the only difference was the variation in relative humidity and dew on canopies.

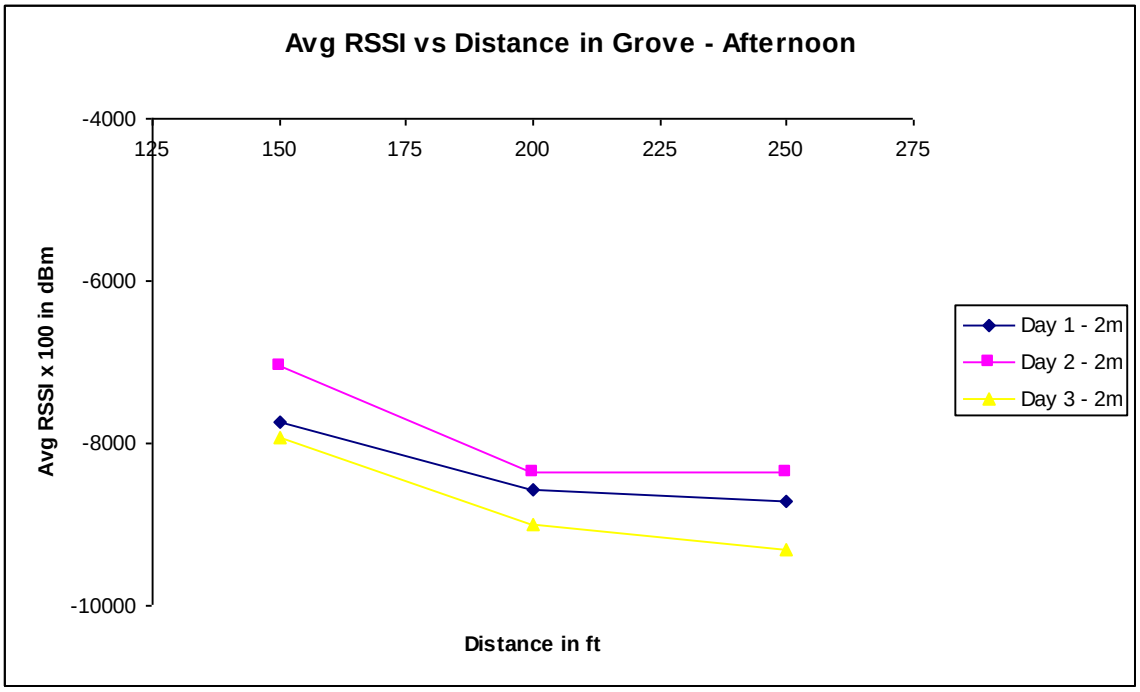

Figure 4-2. Average RSSI vs. distance in grove at 2 m height - Afternoon

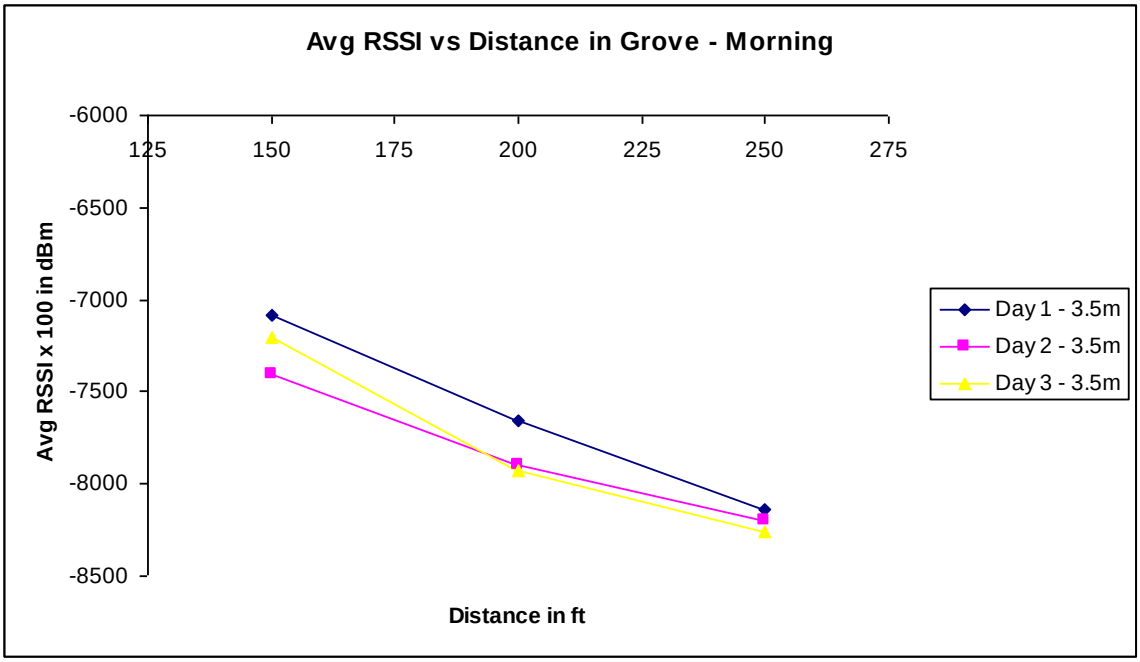

Figure 4-3. Average RSSI vs. distance in grove at 3.5 m height - Morning

Figures 4-3 and 4-4 show the average RSSI values against distance when conducted in the morning and afternoon at 3.5 m height respectively. The data here also indicates the expected decrease in signal strength with increase in distance. The canopies appear to absorb more of the radio signal in the morning when compared to the afternoon.

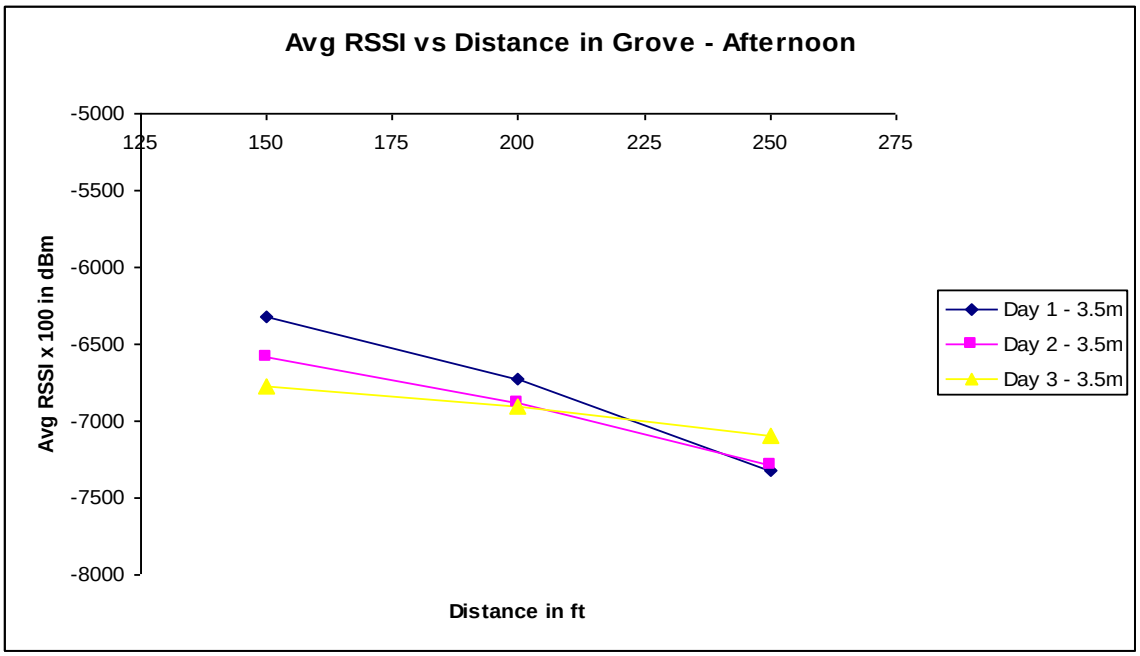

Figure 4-4. Average RSSI vs. distance in grove at 3.5 m height – Afternoon

Similarly, Figures 4-5 and 4-6 show the results of the experiments conducted during the morning and afternoon averaged across each repetition at 0.5 m height. When the moisture present on the canopies is very little or negligible, the signal propagates better than it did when there was moisture. An average difference of 11 dBm existed between the data collected during the morning and afternoon.

The radio propagation is affected by the reflectance characteristics of each agricultural field and is evident from the fact that the signal strength varies from location to location within the grove. The ground vegetation reflects or absorbs some of the signal and has an impact on the capacity of the sensor network. Not only is line of sight a factor but also the height of the nodes

above the ground and foliage are other factors which are to be considered when analyzing radio wave transmission between two nodes.

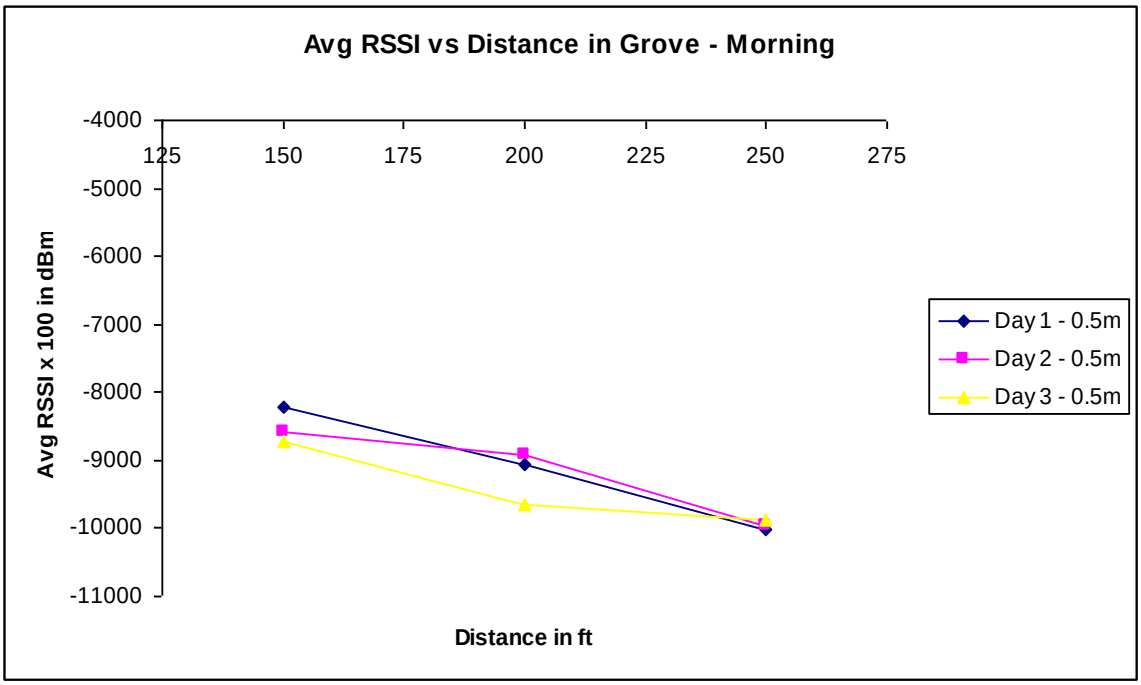

Figure 4-5. Average RSSI vs. distance in grove at 0.5 m height – Morning

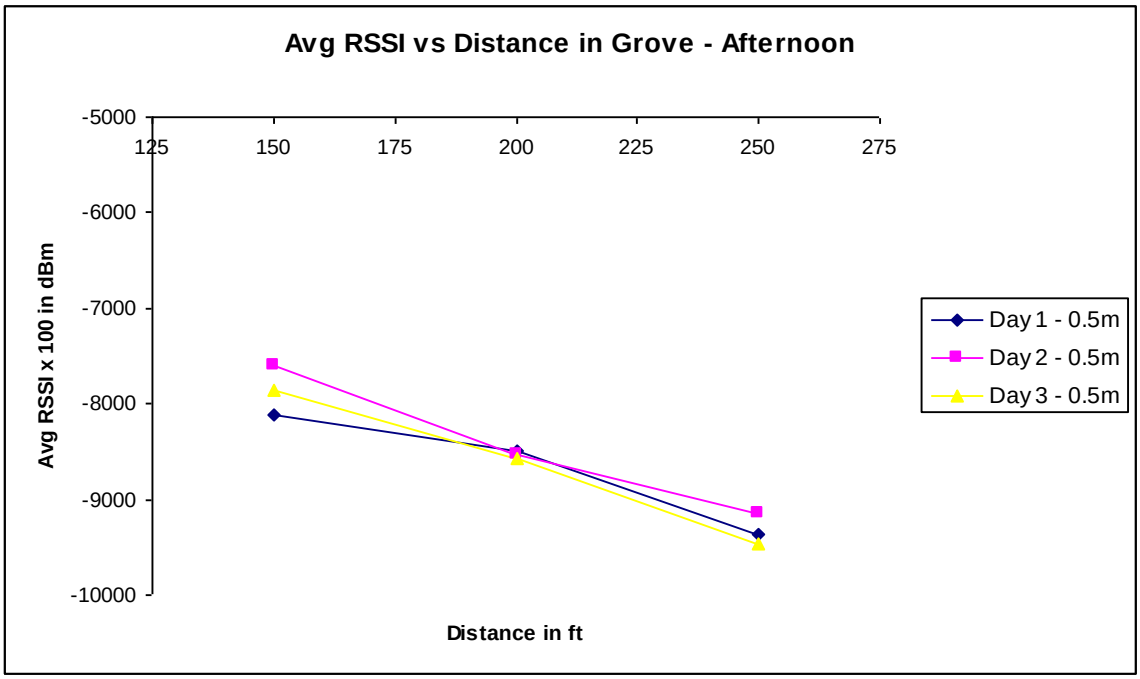

Figure 4-6. Average RSSI vs. distance in grove at 0.5 m height – Afternoon

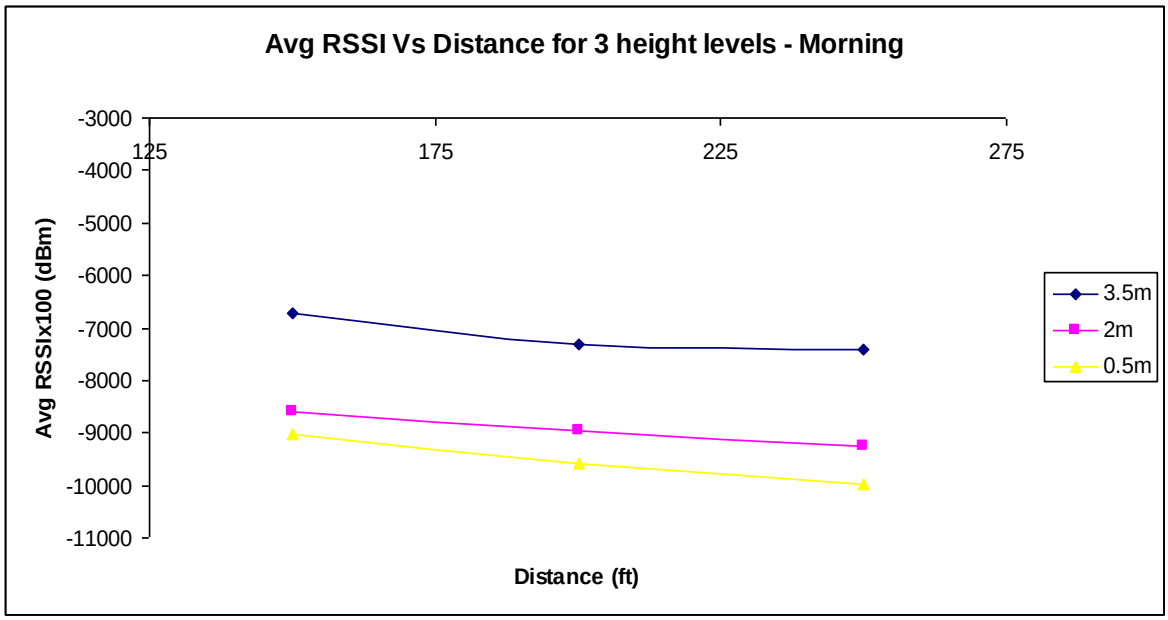

Figure 4-7. Average RSSI vs. distance for 3 height levels – Morning

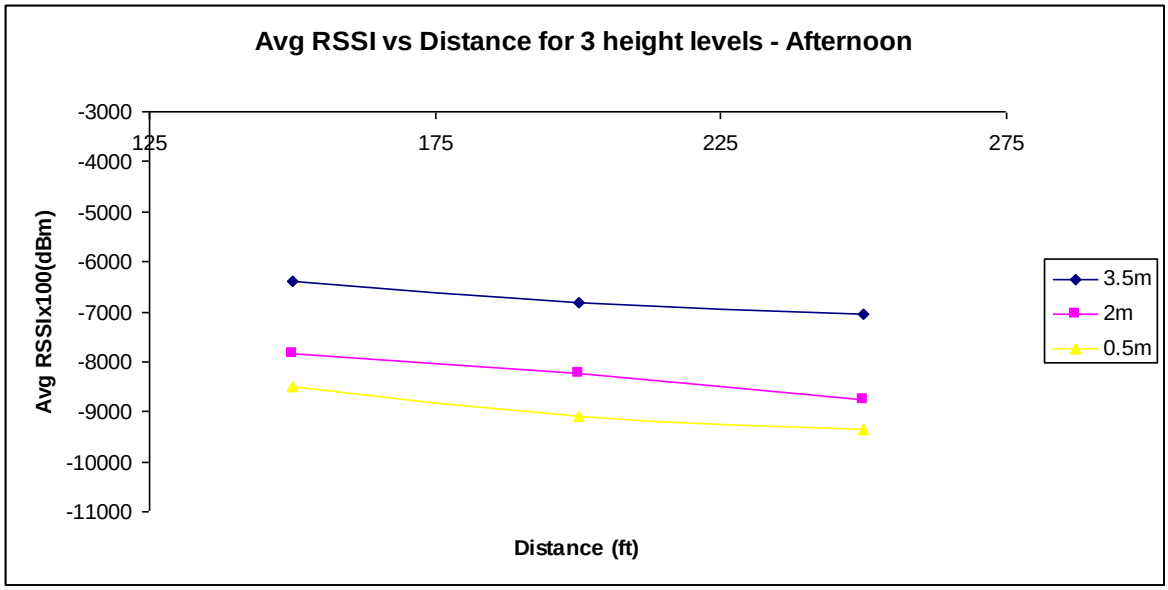

Figure 4-8. Average RSSI vs. distance for 3 height levels – Afternoon

Figures 4-7 and 4-8 show the comparison of signal attenuation of the nodes within the grove averaged across all the three heights taken in the morning and afternoon. Nodes that were placed at heights of 2 m experienced linear signal loss with increase in distance due to signal absorption by canopies.

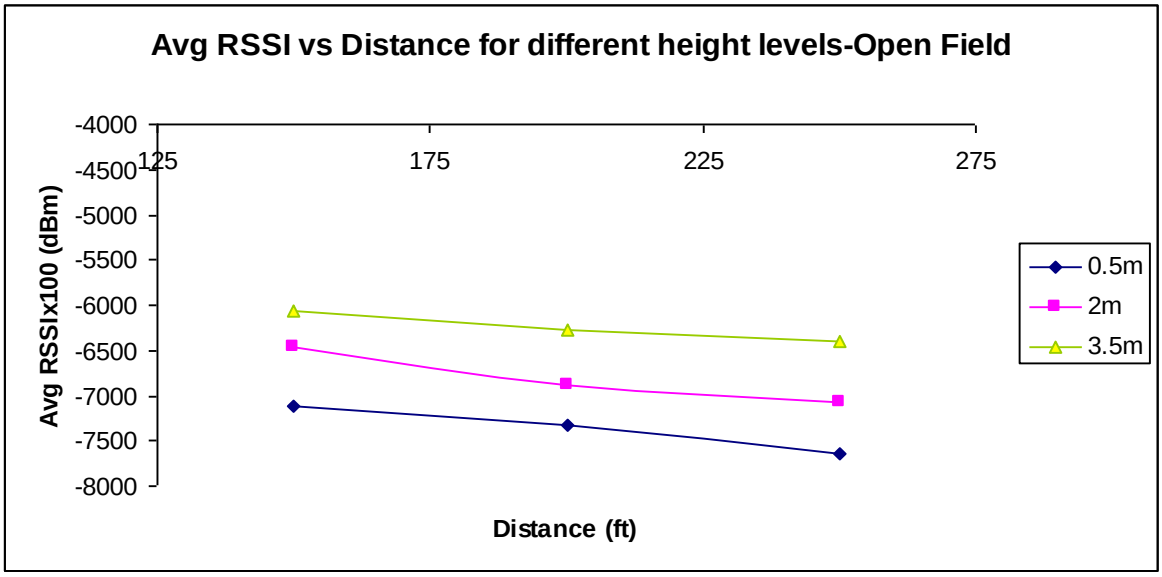

Figure 4-9. Average RSSI vs. distance for 3 height levels in an Open field.

It was noted that the canopy density was maximum at 2 m height for most of the citrus trees in the orchard both along and across the rows. The nodes that were placed at 3.5 m height from the ground observed good signal strength due to the fact that the nodes were above the canopies and absorption was minimal. From figures 4-6, 4-7 and 4-8, it was evident that apart from the tree canopies, the morning dew and relative humidity affected the radio signal strength as there was no change in the experimental setup apart from the variation in these two factors between morning and evening.

Figure 4-9 shows the comparison of signal attenuation of the nodes in an open field environment averaged across three heights. It is evident that there exists some difference in the received signal strength between the data collected in the morning and afternoon within the grove.

Packet Reception Rate

In this work, packet reception rate was calculated from the recorded data and was expressed as percentage. The concept of Fresnel zone is fundamental in wave propagation. The LOS simply

shows the direct path between the two antennas. The pattern of the electromagnetic radiation that is created as a result of signal transmission between the transmitter and receiver is an ellipsoid. This football shaped area (Fresnel zone) the radio waves spread out into after they leave the antenna must be clear, or else the signal strength will weaken as a result of phase cancellation at the receiver end.

Any obstructions that enter into the Fresnel zone reduce the communication range; including vegetation, the ground, etc. As the antennas are placed further apart, the diameter of the Fresnel zone increases and the ground begins to obstruct the Fresnel zone. In order to keep the entire Fresnel zone free of obstructions, it is necessary to raise the antennas (www.digi.com).

It was observed that nodes at height of 0.5 m suffered from signal attenuation and fading due to the fact that the antenna height was less than 60% of the Fresnel zone radius. The packets were mostly absorbed by the ground and trunk of the citrus trees. This was also evident from the packet reception rate in Figure 4-10.

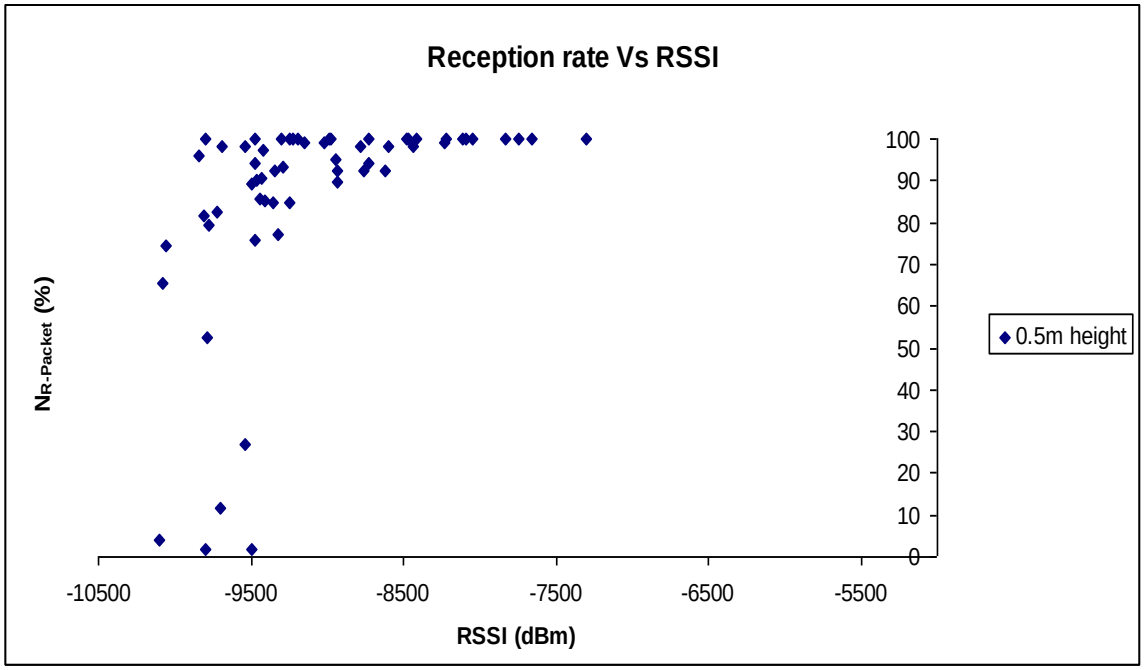

Figure 4-10. Packet reception rate for nodes at 0.5 m height

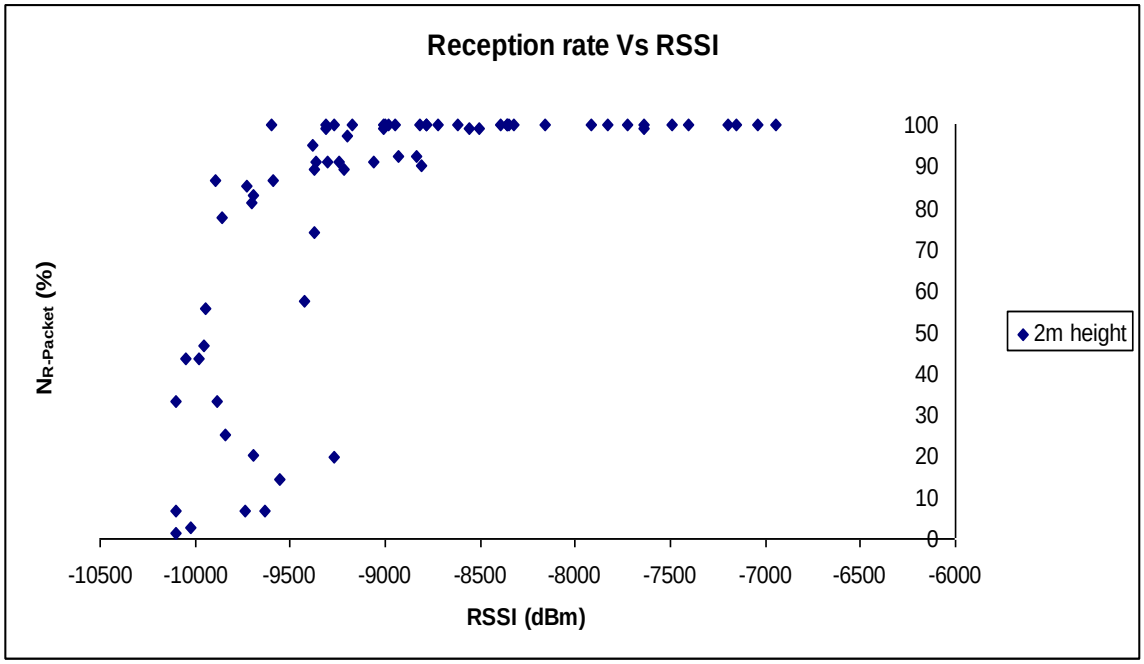

Figure 4-11. Packet reception rate for nodes at 2 m height

Figure 4-11 shows that even though the radio antennas were placed above 60% of the Fresnel zone, radius radio packets were lost and were absorbed by the citrus tree canopies. It was also noted that the tree canopy density was maximum at 2 m height.

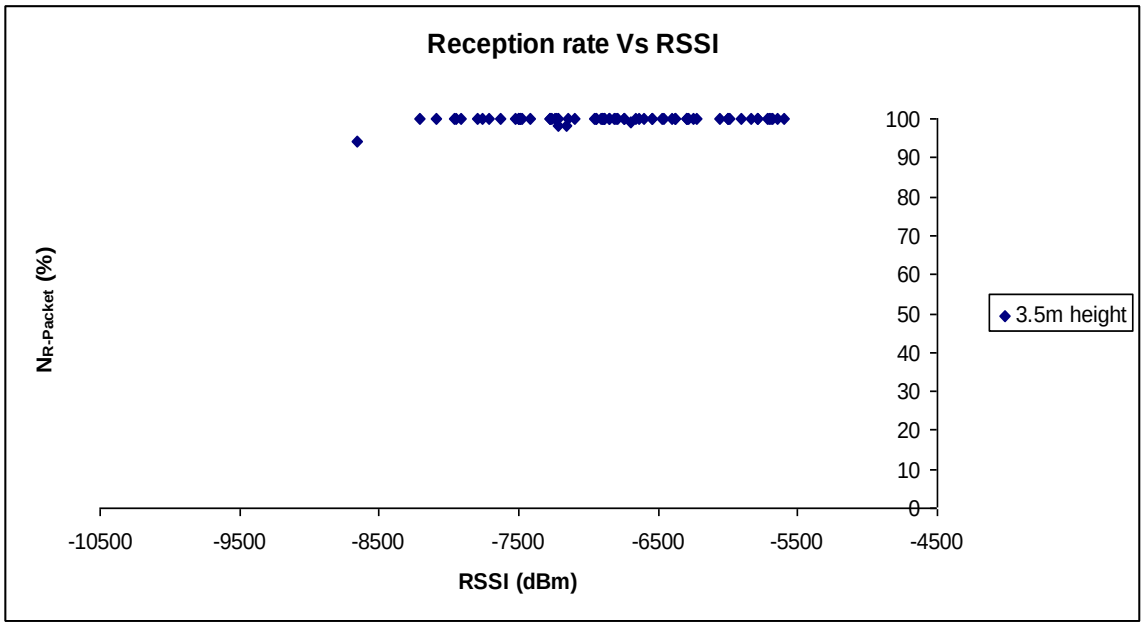

Figure 4-12. Packet reception rate for nodes at 3.5 m height

At 3.5 m height, the radio antennas were above the tree canopies and almost all the packets which were sent by the transmitter were received on the other end. From figure 4-12, it is evident that radio antenna height of at least 60% of the Fresnel radius zone is required if LOS exists.

Experiments were performed in the morning to take into consideration the effect of dew. Table 4-2 shows the measured RSSI values in different environmental conditions. An average difference of 18 dB exists in the RSSI values obtained in the open field compared to the values obtained within grove in the morning. There also exists an average difference of 11 dB with the measured values obtained in the grove at noon compared to the values obtained in the grove in the morning. From table 4-2, it is evident that tree canopies and the dew on the canopies absorb most of the radio signal in the morning.

Table 4-2. Path loss in different environments

Distance (m)	Height (m)	Free Path (dBm)	Vegetated Path (dBm) Morning	Afternoon
	0.5	-69.09	-85.92	-76.09
45	2	-63.06	-83.89	-77.00
	3.5	-62.00	-68.56	-66.32
	0.5	-72.98	-94.61	-84.78
60	2	-70.12	-90.88	-81.52
	3.5	-64.19	-71.91	-70.86
	0.5	-77.20	-99.60	-93.15
75	2	-72.68	-100.50	-91.39
	3.5	-61.55	-79.43	-75.25

In order to determine the effect of citrus tree canopy on the different height levels, 0.5 m and 2 m RSSI values were collected and t-test was performed to determine which height level was significant. The 3.5 m height was not considered for this analysis. From the t-test, it can be concluded that there is significant difference in the mean RSSI values for the two height levels considered in the field. From table 4-3 and 4-4, it is observed that nodes at 2 m height on an average have better signal strength compared to the nodes at 0.5 m height.

Table 4-3. Paired t-test assuming unequal variances

	0.5m	2m
Mean	-7784.279412	-7329.691176
Variance	2141997.1	1335717.47
Observations	68	68
Hypothesized Mean Difference	0	
df	127	
t Stat	-2.010137108	
P(T<=t) one-tail	0.02326759	
t Critical one-tail	1.656940344	
P(T<=t) two-tail	0.046535181	
t Critical two-tail	1.978819508	

Table 4-4. Paired t-test two sample for means

	0.5m	2m
Mean	-7784.279412	-7329.691176
Variance	2141997.1	1335717.47
Observations	68	68
Pearson Correlation	0.902143696	
Hypothesized Mean Difference	0	
df	67	
t Stat	-5.744736599	
P(T<=t) one-tail	1.22526E-07	
t Critical one-tail	1.667916115	
P(T<=t) two-tail	2.45051E-07	
t Critical two-tail	1.996008331	

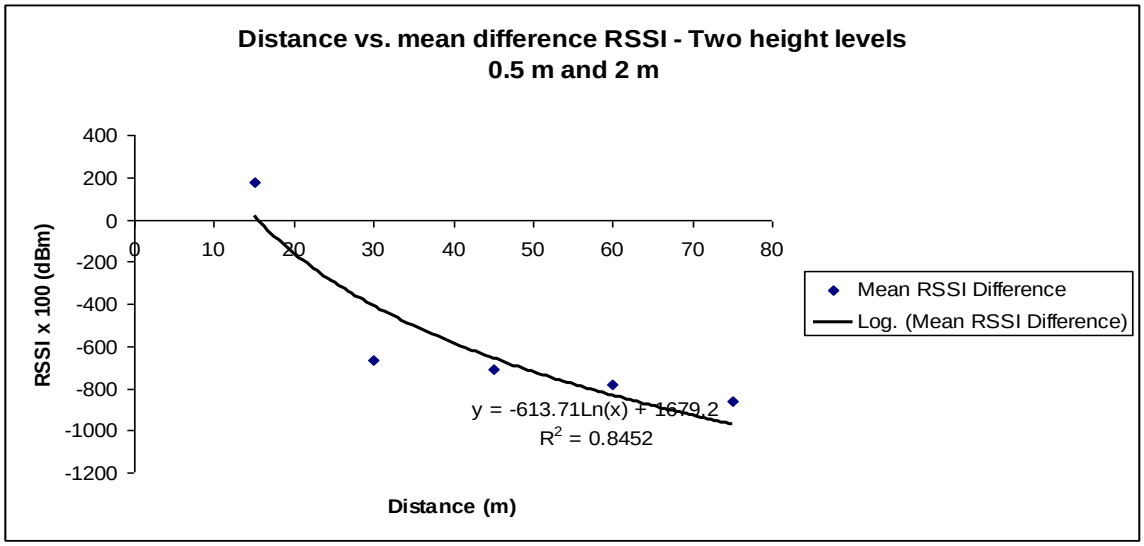

Figure 4-13. Distance vs. mean difference RSSI for 2 height levels (0.5 m and 2 m)

From figure 4-13, it is observed that 0.5 m height has better signal strength at 15 m distance, but for longer distances, 2 m height appears to have better signal strength. For shorter distances and low height, the effect of tree canopy is minimal. As distance increases, the surface loss is significant for lower heights compared to the vegetation loss. Thus, with increase in distance, it is better to have the node placed at 2 m height than at 0.5 m height.

Path Loss Model

Considering the model under study, it is an empirical model developed from an earlier ITU-R recommendation where the attenuation is calculated based on the distance between the nodes (vegetation depth), their frequency, and height from the ground. In this analysis, the individual losses namely the surface loss and foliage loss were calculated separately for all heights and distances, and were added to determine the total path loss during afternoon conditions. From equation (11), the total path loss within the citrus grove is calculated.

$$Total\ Path\ Loss\ (dB) = 40\log{}^{*}R - 10{}^{*}\log G_T - 10\log{}^{*}G_R - 20{}^{*}\log h_t - 20{}^{*}\log h_r + 15.6 * (f^{-0.009}) * (d^{0.26})$$

Data was collected at four different distances within the field to validate the model. The model performed reasonably well for all distances and height levels which were considered within the field.

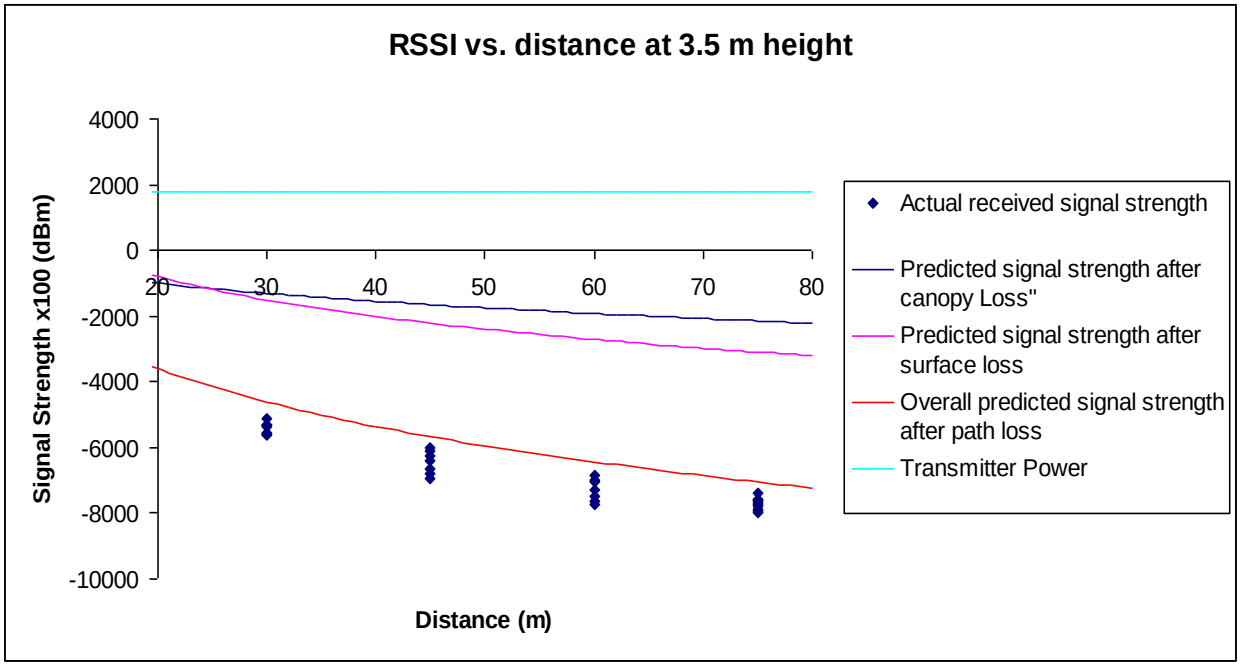

Figure 4-14. Predicted vs. actual signal strength at 3.5 m height.

The inconsistency in the actual received RSSI values was due to the intrinsic nature of transceiver variability. Transmitter variability occurs in practice when a transmitter is programmed and set to send out packets at a specified power level of ‘x’ dBm, it not necessarily sends out packets at the specified power level but at a value very close to x. Receiver variability occurs when different receivers record different RSSI measurements even when all parameters that affect signal strength are kept constant.

From Figure 4-14, because of the actual received signal variability, the model has an RMS error of 10.86 dB against the measured data at 3.5 m height. Figure 4-15 and 4-16 show the model performance at 2 m and 0.5 m height. The model has an RMS error of 8.56 and 5.32 dB against the measured data at 2 m and 0.5 m height.

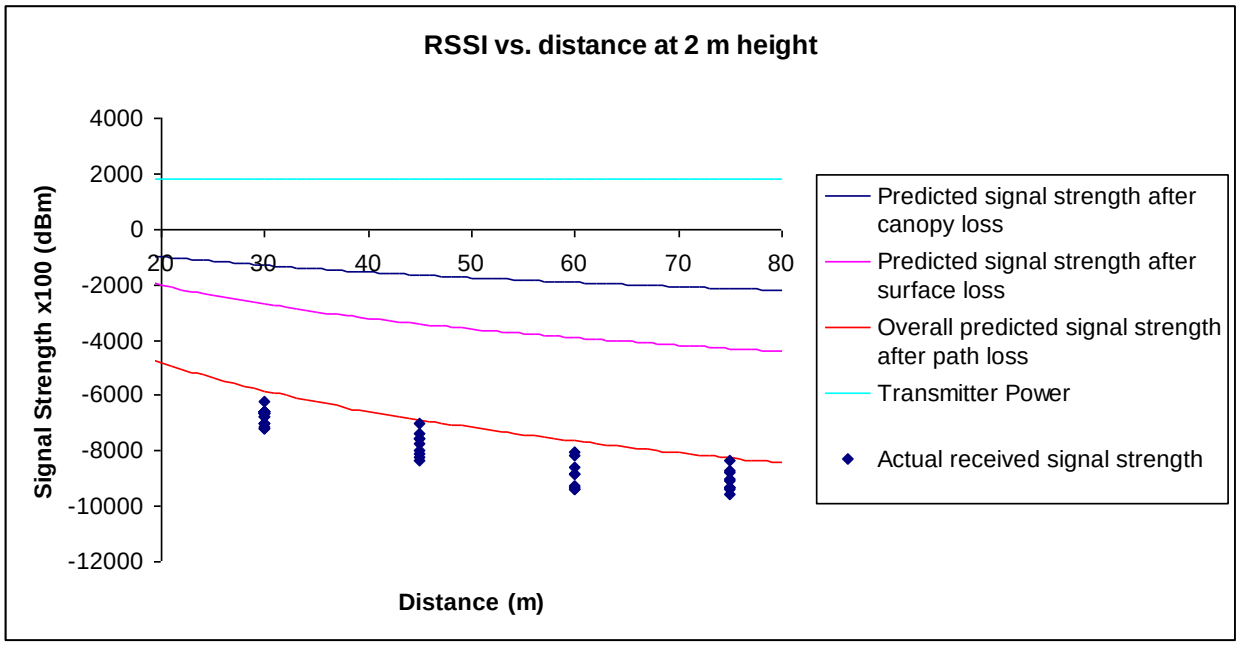

Figure 4-15. Predicted vs. actual signal strength at 2 m height

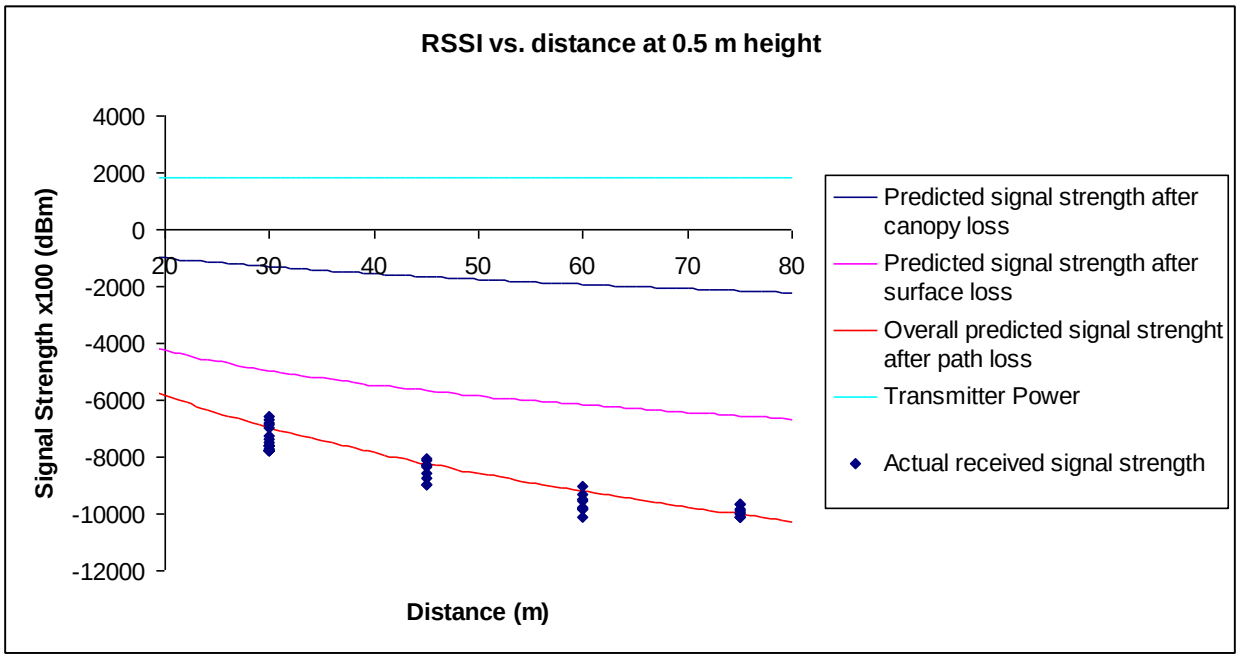

Figure 4-16. Predicted vs. actual signal strength at 0.5 m height

Figures 4-14, 15 and 16 shows the predicted received signal strength by calculating the path loss (surface loss + foliage loss) and subtracting the transmitter power from the loss. The predicted signal strength using surface loss alone and foliage loss alone are also shown in all the

graphs. The path loss caused by the surface of the earth alone is calculated from the surface loss model and the transmitter power is subtracted from this loss to predict the received signal strength using surface loss alone. Similarly, vegetation loss is used to predict the received signal strength within the grove. It is observed that the individual losses do not have a good accuracy in predicting the received signal strength and the model performs relatively better when the path losses are added together. It is also observed that the surface loss is greater compared to the vegetation loss.

The current model under study is a composite model comprised of surface loss and foliage loss. It is vital to compare the current model results with other existing models. Therefore, model under study was compared against different existing foliage path loss models at similar frequencies.

It was observed that the other foliage loss models over predicted the actual RSSI value by close to 10 dB. From the analysis, it was observed that the composite model under study performs reasonably well in terms of accuracy during the afternoon. An improved comparison would analyze each model for the same grove environment and frequency, and consider the effect of morning dew for predicting the path loss in the morning but this was beyond the scope of the study.

Effect of Relative Humidity on RSSI

Weather information was recorded separately to analyze the effect of relative humidity. In order to analyze the effect of relative humidity on signal strength, distance and height were kept constant and the signal strength was analyzed against varying relative humidity.
Data was collected in the morning and in the afternoon to account for the changing relative humidity. Figure 4-17 and 4-18 show the plot of relative humidity against signal strength at 2 m height - 60 m distance and 0.5 m height - 30 m distance.

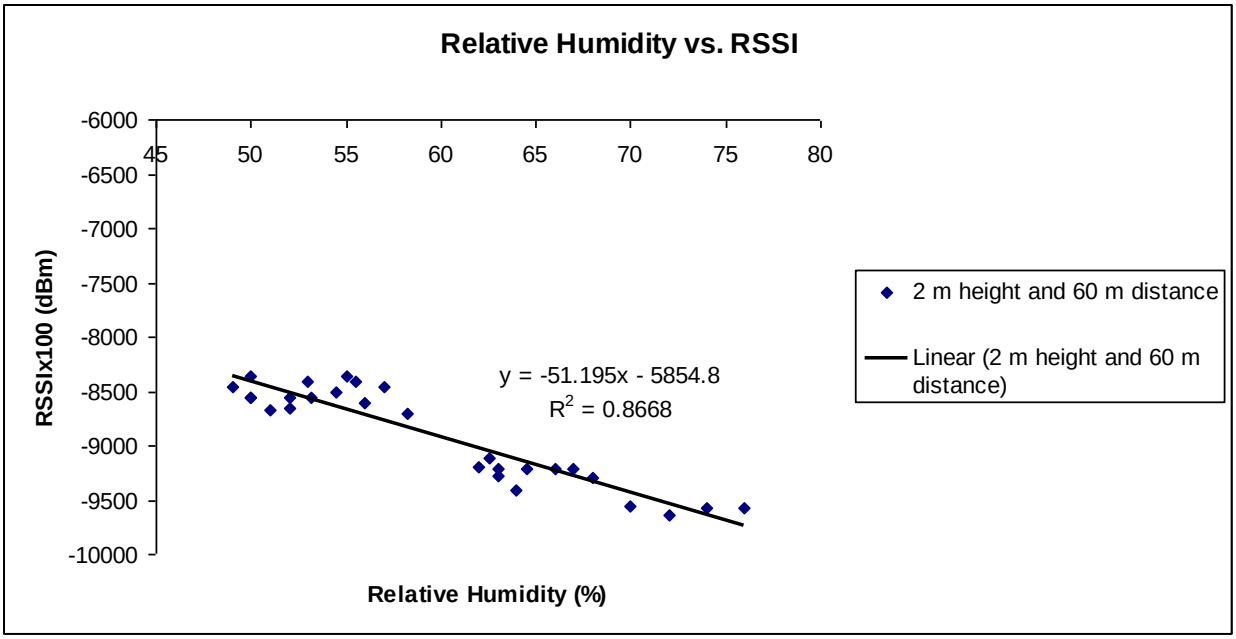

Figure 4-17. Relative humidity vs. RSSI at 2 m height and 60 m distance within the grove

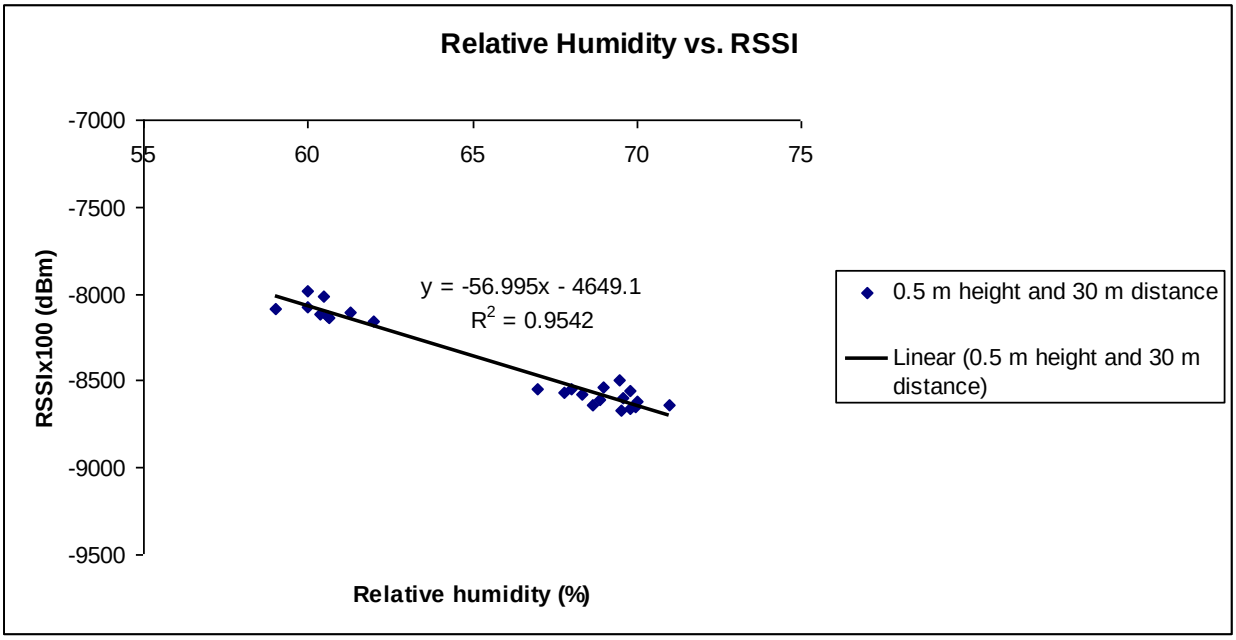

Figure 4-18. Relative humidity vs. RSSI at 0.5 m height and 30 m distance within the grove

From figure 4-17 and 4-18, the linear decrease in signal strength as the relative humidity increases is observed. Comparing the RSSI values across all the different heights against relative humidity, shows the general trend of decrease in signal strength as relative humidity increases.

The RSSI data again can be grouped based as morning or evening from the graph just by ordering them based on relative humidity. The RSSI values do not show any specific trend or pattern when compared with temperature.

CHAPTER 5
CONCLUSION

From the analysis performed on the data collected at the North-40 grove, Lake Alfred, it can be concluded that the signal strength of the ZigBee radios was affected by the direction of the placement of the nodes (orientation of the antennas), distance between the nodes, and their height from the ground. Considering non-line of sight deployment of nodes (0.5 m and 2 m height level from the ground), the nodes suffered from signal attenuation caused by the ground and tree canopies. From the study, it can be recommended that for the transmitter and receiver distances up to 20 m, 0.5 m height can be used for communication purposes. Beyond 20 m, 2 m height can be used, as at lower height and longer distances; the surface loss was significant compared to the vegetative loss. For LOS deployment of Zigbee nodes, the nodes performed well with a clear LOS at 3.5 m height within the grove.

An average loss of 11 dB in signal strength was observed for intra-day measurements. This loss could be attributed to the morning dew on the canopies and the difference in relative humidity during the morning and afternoon periods. There also existed an average loss of 18 dB in signal strength when the open field data was compared with the citrus grove data in the morning.

Weather information was documented to analyze the effect of temperature and relative humidity on ZigBee radios showed that the radios were affected by relative humidity. The data formed separable groups based on the relative humidity. However, the rate of increase in signal strength per unit decrease in relative humidity could not be evaluated. The temperature did not have any significant effect on the signal strength.

A composite model was used to predict the signal strength within a grove during the afternoon period. The model yielded satisfactory results in terms of accuracy in predicting signal

strengths for outdoor grove environments. The current model was fairly simple and accurate requiring moderate amounts of site information. A complicated composite model which requires detailed site specific information may result in more accurate predictions of signal strengths. One of the major limitations in using a complicated composite model would be an increase in computation time. Hence, a simple composite model, developed in this study, lends a possibility of using simpler and less sophisticated models to predict path loss, and further helps in planning and deployment of ZigBee based wireless networks within citrus groves.

APPENDIX A
DEVICE CONNECTIONS AND CONFIGURATIONS

This appendix gives an overview of the application interface boards for the ZigBee / IEEE 802.15.4 XBee wireless network transceivers, device connections and configurations.

ZigBee and AppBee-Mod Board Features

ZigBee is an established set of specifications formulated under the relevant task force IEEE 802.15.4 and is the global standard of communication protocol for wireless personal area networking. The ZigBee alliance was formulated during the same time the IEEE 802.15.4 work group was formulated in 2004. Today the marketable name for this technology is ZigBee. The main goal of this technology is quite different from that of personal wireless area networks, i.e. instead of offering high data rates for long distances with high QoS, they intended to work in the ISM band with very low power consumption and cost requirements, and intended to serve the industrial, medical and residential applications. The star, tree and mesh topologies are supported by the ZigBee network layer. In a star topology, the network is controlled by one single device called the ZigBee coordinator, which act as a router to other networks. It stores information about the network in the form of routing tables. The Full Function Device (FFD) is an intermediary router, transmitting data from other devices. It needs lesser memory when compared to the coordinator node and can operate in all topologies and can also act as a coordinator node.

The Reduced Function Device (RFD) is a device just capable of talking in the network. It does not have routing functionality and requires much less memory. The RFD only talks to the network coordinator. The RFD is cheaper and easier to implement than the FFD. The standard ZigBee feature is its low power consumption which is required for two major modes of operation -Tx/Rx and sleep. They operate on the three license free bands: 2.4-2.4835 GHz, 868-870 MHz

and 902-928 MHz. Maximum data rates allowed for each of these frequency bands are fixed as 250 kbps at 2.4 GHz, 40 kbps at 915 MHz, and 20 kbps at 868 MHz. Depending on the topology used, data may be sent to individual nodes (point-to-point), or to all nodes in range (point-to-multipoint) using a broadcast address. The devices use clear channel assessment (CCA) on a CSMA/CA network which helps ensure devices do not talk-over one another. In point-to-point communications, error checking, acknowledgements and retries are used to ensure data delivery. The use of flow control (RTS) helps ensure devices, such as the BASIC Stamp, do not miss incoming data.

AppBee-Mod is an application interface board that connects to the AppMod dual row 20-pin header of many Parallax BASIC Stamp boards for power and quick communications to the BASIC Stamp.

Table A-1. Key Xbee features from Maxstream's documentation

	X-Bee	X-Bee Pro
* Range - Indoor	100 ft (30m)	300 ft (100m)
* Range – Outdoor	300 ft (100m)	1 mile (1500m)
Transmit Power	0 dBm (1mW)	20 dBm (100mW)
Receiver Sensitivity	-92 dBm	-100 dBm
TX Current	45mA	214mA
RX Current	50mA	55mA
Power-Down (Sleep) Current	<10uA	<10uA

* Ranges are line of sight and height dependent.

Key X-Bee Features

- IEEE 802.15.4 compliant, Low-Rate Personal Area Networking.
- 2.4 GHz DSSS (Direct Sequence Spread Spectrum).
- 250,000 bits per second.
- Acknowledgement and reties.
- Addressable, > 65,000 addresses available.
- Point-to-Point and Point-to-Multipoint (broadcast) messaging.
- Channel and Network ID selectable for cluster separation.
- Fully configurable via serial commands.
- Transparent transmission and reception.
- Receiver Strength indication.
- Free X-CTU interface software.

AppBee Features

- On-board 3.3 V regulator and 5 V conditioning
- Supplied power range from 5 V to 12 V
- Send and receive LED's
- Communication from serial devices (BASIC Stamp, etc), or from a PC using parallax's USB2SER USB to serial converter for direct PC data acquisition and control or using MaxStreams X-CTU software.

Device Connections and Communications

The XBee unit handles the packaging of data for transmission and error checking and acknowledgements on reception. All that is required is to send the device serial asynchronous data (9600, 8-N-1 by default) for transmission and accepting data addressed to that particular node. For simple data flow all that is required is data sent to Din and accepted from Dout. RTS may be enabled so that the XBee does not send data it received via RF before the interfaced device is ready to accept the data. By default, all devices are at address 0 and send to address 0. With a little coding addresses may be changed and flow control may be added. The table below shows all the necessary boards and software required for deploying a ZigBee based multi-node wireless network.

Table A-2. Hardware and software requirements along with functionality

Board & Software Requirements	Functionality
AppBee Mod board	Reduced end function device
Parallax Propeller Protoboard	Controller logic
AppBee SIP-LV	Plugged into controller board for communication with end nodes
AppBee Proto board	Plugged into controller board for communication with base device
SelmaDAQ	Real-Time Data Acquisition tool software add-in for Microsoft Excel
Propeller Tool Software v 1.2.6	IDE using spin
Prop-Plug	USB-to-serial port connection

Board Assembly

AppBee Mod Board - Reduced Function End-Node

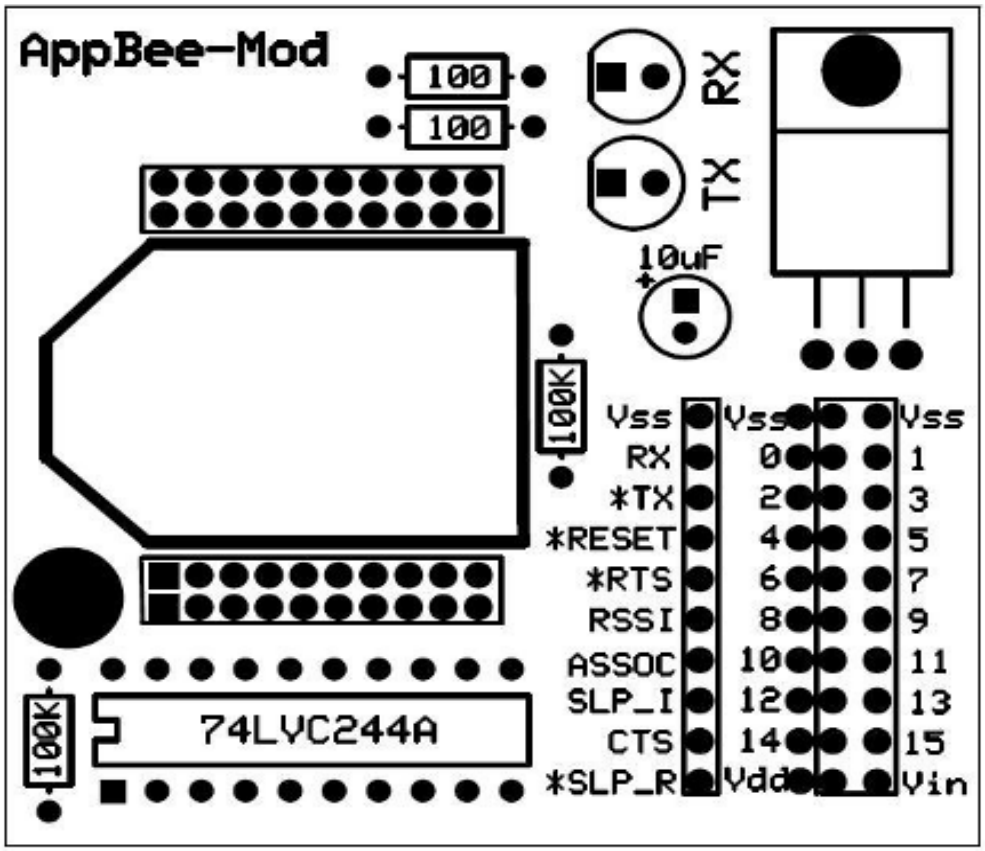

Figure A-1. Board pic of AppBee-Mod

Figure A-1 shows the board pic of the AppBee-Mod board which was used for the experiment. All the necessary parts for setting up the board are mentioned in the table below along with all part numbers.

Table A-3. Products with part numbers

DigiKey Part Number	Product
LM2937ET-3.3-ND	3.3V regulator
P966-ND	10uF cap
S5751-10-ND	10 pos 2mm header, 2 per board
377-1549-ND	9V Battery clips
100QBK-ND	100 ohm resistors for LEDs, 2 per board
516-1319-ND & 516-1316-ND	Red & Green LEDs
	Jumper wire for loopback

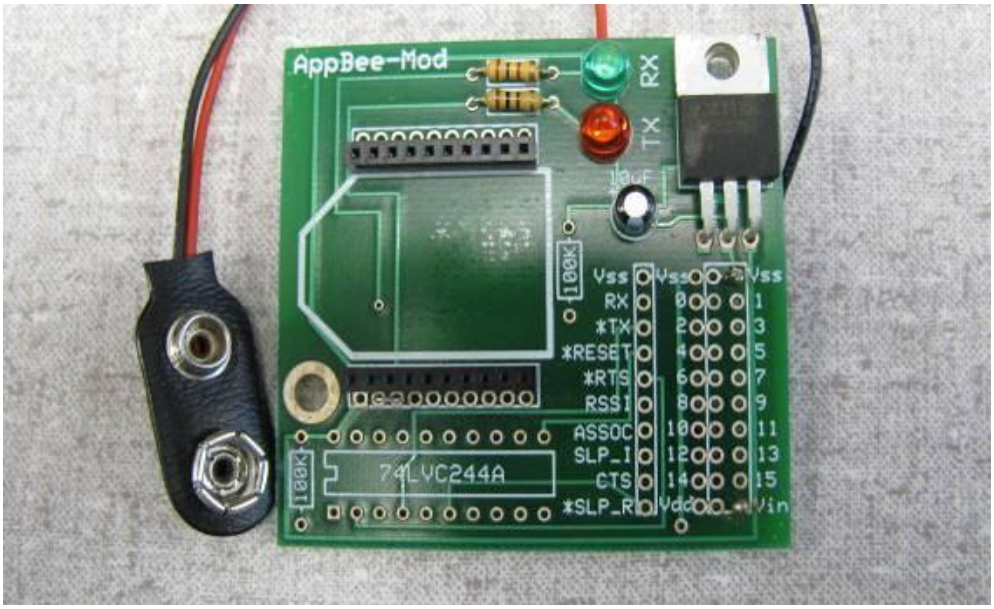

Figure A-2. Assembled AppBee-Mod board

Figure A-2 shows the assembled Appbee-Mod board. All the parts mentioned above have been soldered in the board and a jumper wire is soldered from pins 2-3 on the X-Bee holder.

Parallax Propeller Proto-Board

A Parallax Propeller Protoboard was used as the collector intelligence with AppBee boards mounted on it. Figure A-3 shows the plain parallax propeller board.

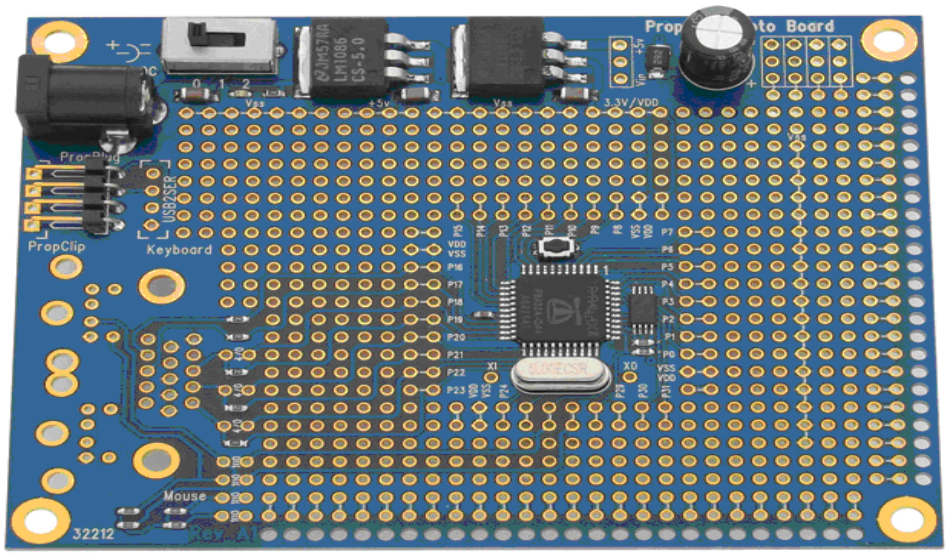

Figure A-3. Parallax propeller proto-board

The parallax propeller board is assembled as shown in figure A-4.

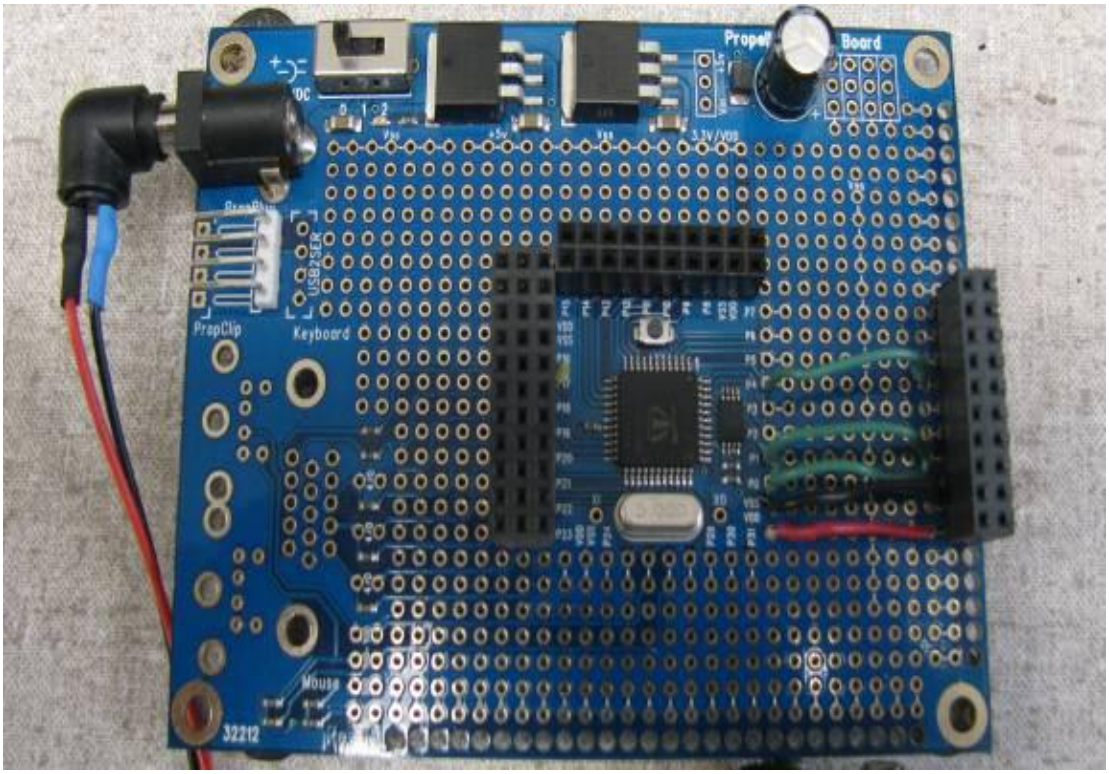

Figure A-4. Assembled parallax propeller proto-board

AppBee-SIP-LV and AppBee Proto Board

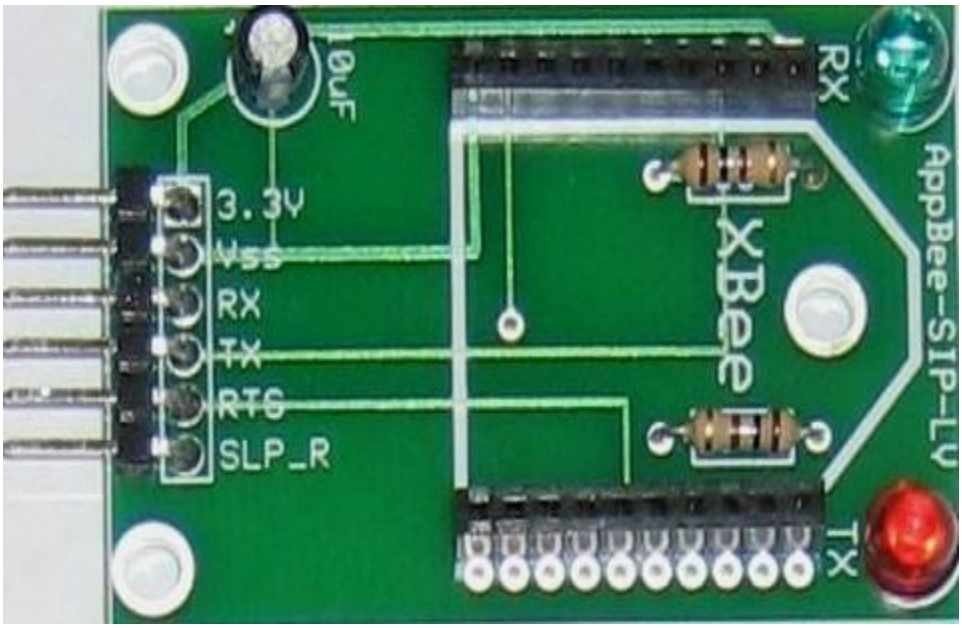

Figure A-5. AppBee-SIP-LV board

The AppBee-SIV-LV board was used for communication with the base Xbee pro transceiver. A X-Bee pro node was plugged in to this board. The AppBee-SIP-LV board was plugged in to the propeller proto-board.

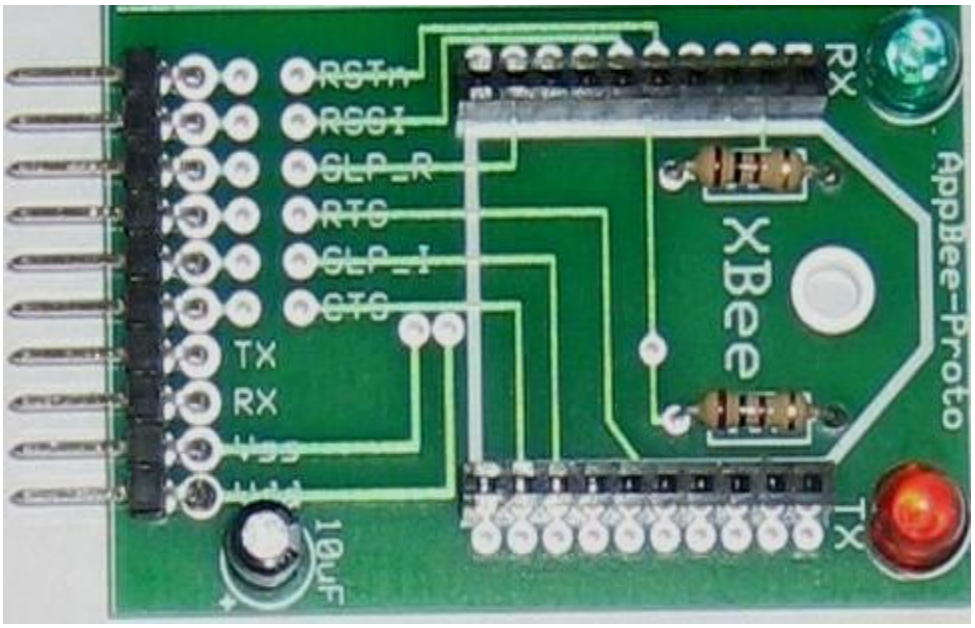

Figure A-6. AppBee-proto board

The AppBee proto board is used for communication with the end-nodes in the field.A default X-Bee pro node is plugged into this board. The AppBee proto board is plugged into the propeller proto-board.

Software Configuration and Installation

SelmaDAQ Software

The SelmaDAQ is a real-time data acquisition tool software add-in for Microsoft Excel. Once installed, it also provides the basic control APIs for communication with the base XBee connected to the PC.

X-Bee Configuration

The XBee may communicate to a personal computer (PC) via USB using Parallax's USB2SER device. The XBee units have numerous settings for configuration, two of which are:

- MY – The node's own address (16-bit)
- DL – Destination Low (16-bit)

By configuring these, a node is given an address, and a node to communicate to. For example, for node 0 to send data to node 1:

- MY = 0
- DL = 1

The data will be delivered with error checking, an acknowledgement, and up to 3 retries if needed. For node 2 to send data to node 0:

- MY = 2
- DL = 0

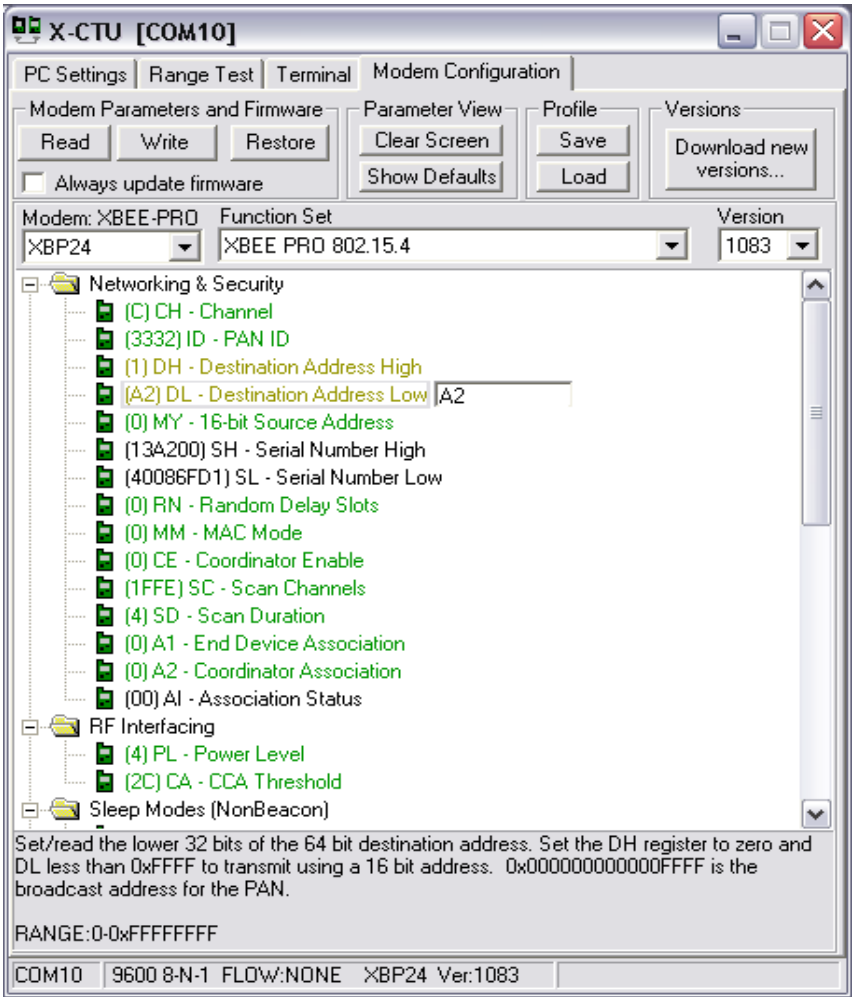

Figure A-7. X-CTU software for configuring X-Bee Pro's

Figure A-7 shows the configuration tab from the X-CTU software using the USB Base device. Once the device is read (READ button), settings are modified and new settings downloaded using the WRITE button.

Figure A-8. Laptop/PC base XBee Pro

Figure A-8 shows the USB device used to configure the X-Bee nodes using the XCTU software in the PC.

Procedure for Configuring X-Bee Node

Plug in the USB board (with X-Bee plugged in on top) to the system.

- Open X-CTU software and select the appropriate COM port.
- Access its properties by navigating to the Modem Configuration tab and
- Click on the read parameters button to get the current device settings.
- Change the MY address and DL according to requirement.
- Click on the write parameters button to upload the new settings to the device.

Once the X-Bee is configured, it can be plugged on to the AppBee-Mod board. The board is powered using a 9V battery.

Procedure for Testing Parallax Propeller Proto-Board

- Using this propeller tool software IDE, the binary .spin object file is compiled and loaded onto the parallax propeller proto-board.

- Once the parallax proto-board (controller board) is setup as shown in the figure, it can be tested for communication between excel and the Propeller proto-board by keeping the Prop-Plug connected.

Figure A-9. Prop-plug

- Plug the AppBee proto board (along with a default X-Bee Pro) at a 90 degree angle on the header on the edge as shown in the figure.

- Note down the COM port the proto-board is on through the propeller software. Select the same address in the Excel data acquisition module and try to connect with the proto-board. It takes about 20 seconds before it display's the message ready to collect.

- Once this message is appears on the display area of the data acquisition module, the proto-board is ready for data acquisition.

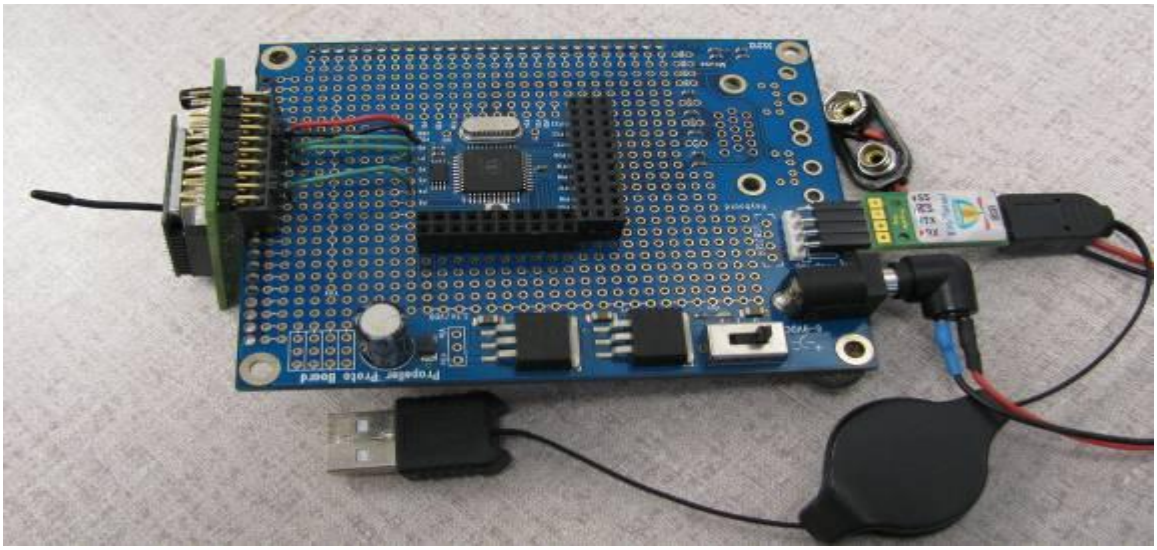

Figure A-10. Parallax propeller proto-board with AppBee proto board and prop-plug connected.

Data polling algorithm:

Pub Start | check

- ' initialize communications
- ' configure Base Xbee
- ' Configure Collector Xbee
- ' main loop
- ' repeat DestAddr from 1 to endAddr
- ' if transmit status, then poll units
- ' check again each loop
- ' accept AT status
- ' send string to addr 2
- ' accept TX status
- ' accept returned data if any
- ' send data to Excel
- ' check for Excel data
- ' waste time between sets waiting for Excel data

Pub AcceptData

'This section accepts data from the collector Xbee and determines from API packet type and appropriate action.

- ' RX data - Echo'd data
- ' increase return count
- ' record RSSI level
- ' AT response
- ' tx Status - see if ack'd

Pub RxBase(time) | Val

- ' Receives data from PC
- ' based on vaue different actions taken
- ' Start polling
- ' stop polling
- ' set end address
- ' set time between sets

Pub SendSelmaDAQ | ptr

- ' assemble strings to send to base

Once the code is loaded on the propeller proto-board, the parallax board can be put together by plugging in the AppBee-SIV-LV (with a default X-Bee Pro) on the left side of the chip as shown in the figure below.

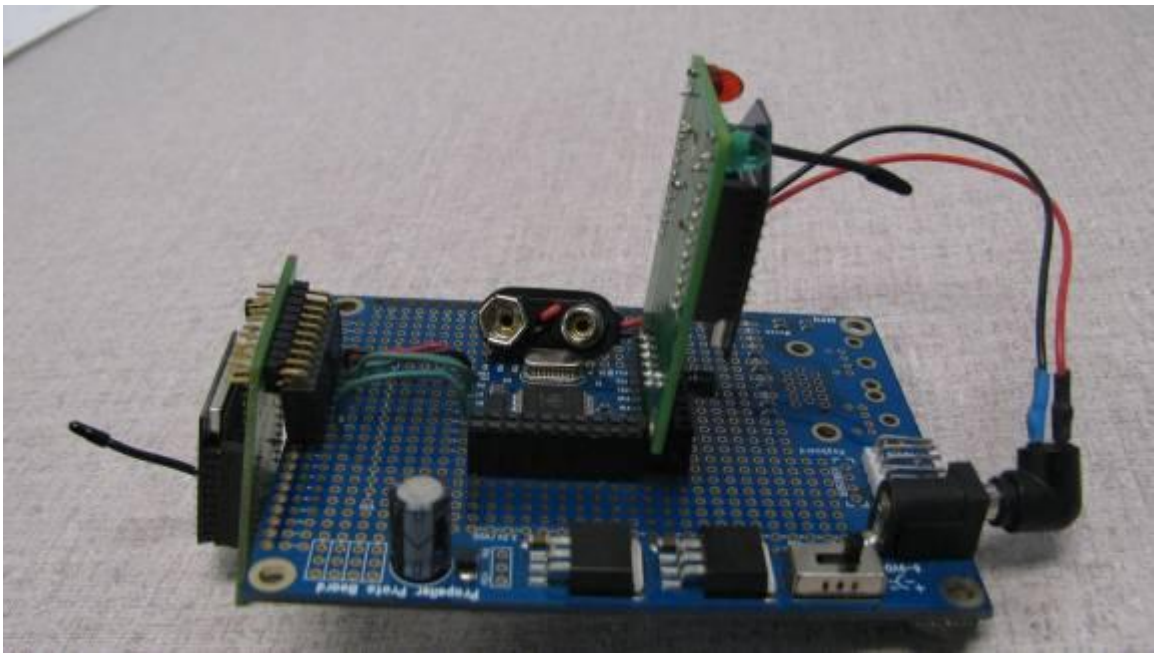

Figure A-11. Parallax propeller proto-board with AppBee boards connected

- Line up the pins for Vdd, Vss, P16, P17 etc.
- Ensure the adapter board goes 3.3V to Vdd, etc.
- Configure the proto-board in such a way that P16 and P17 are the receiver and transmitter pins, so when you line up the pins for Vdd and Vss Rx and Tx pins of the AppBee-SIV-LV board line up on P16 and P17 of the proto-board.
- Once this has been done, the configuration for the parallax propeller proto-board is over.
- Figure A-11 shows a picture of the parallax propeller proto-board with both the AppBee boards plugged in.

Procedure for Setting up all the Boards for Data Collection

Once all the boards have been soldered as shown in the respective pictures, the X-Bees need to be configured in the following manner.

- The Laptop/PC base XBee - set to Address FF on PANID - 3332

- The remote units are set to Address 2 and PANIDs starting from 1, 2 ... [depending on number of remote units]
- The Xbees on the controller board are left with their default values as they are being set in the code with MY Addresses 0 and 1.
- Power up all the end-nodes and the collector board using 9V batteries.
- Insert the PC base XBee into the laptop usb port and open the Excel StampDAQ macro.
- Determine which COM port is being used and select the same port on the StampDAQ and click on the connect button.
- Once connected the appropriate display message appears in the StampDAQ
- Enter the appropriate number of end-nodes in the StampDAQ and set the time delay between successive readings.
- Clear all the cells and counters and hit the Start Polling button.
- All the data is recorded on excel in the following format shown below.

Time	**Seconds**	**Addr**	**RSSI**	**Total Sent**	**Ack**	**Returned**	**Ave RSSI x 100**

APPENDIX B
SIGNAL STRENGTH PREDICTION

This appendix provides the details for predicting the signal strength using the composite model. The theory behind predicting received signal strength is to first determine the total path loss and subtract the path loss from the transmitted power.

In order to determine the total path loss, a composite model (based on theoretical models) was developed. The composite model comprised of a surface loss model and a foliage loss model. The individual losses are added together to determine the total path loss the radio wave experiences when it travels from the transmitter to the receiver.

The total path loss is given by the following equation

$$Total\ Path\ Loss\ (dB) = 40 \log^{*} R - 10^{*} \log G_T - 10 \log^{*} G_R - 20^{*} \log h_t - 20^{*} \log h_r + 15.6 * (f^{-0.009}) * (d^{0.26})$$

The path loss caused by the reflection of radio wave on the surface of the earth is given by the equation (1) shown below.

$$P_L = 40 \log R - 10 \log G_t - 10 \log G_r - 20 \log h_t - 20 \log h_r \qquad (1)$$

The path loss caused by the citrus tree canopies is given by the equation (2)

$$P_L = 15.6*(f^{-0.009})*(d^{0.26}) \qquad (2)$$

where, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, R is the distance between the transmitter and receiver (m), h_t is the height of the transmitting antenna (m), h_r is the height of the receiving antenna (m), P_T is the transmitter power (18 dBm), f is the frequency used (2.4 GHz - $2.4 * 10^9$ Hz) and d is the vegetation depth (m).

Steps for Predicting Signal Strength

For example, in order to predict the signal strength at 50 m distance and at 2 m height within the grove, the path loss is first calculated using the above path loss equation.

Parameters:

- R, d – 50 m;
- h_t, h_r – 2 m;
- Antenna Gain = 10* log G_T = 10* log G_R = 1.5 dBi;
- f = frequency used (GHz) = 2.4 * 10^9 Hz;
- P_T = Transmitter Power = 18 dBm
- The path loss calculated using (1) = 52.91 dB (Surface)
- The path loss calculated using (2) = 35.51 dB (Vegetation)
- The total calculated path loss (1) + (2) = 88.42 dB
- The signal strength at the receiver node would be $P_T – P_L$;
- $P_R = 18 – P_L$
- P_R = 70.42 dBm

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BIOGRAPHICAL SKETCH

Raghav Panchapakesan was born in 1983 to R.Panchapakesan and S.Mohana in Thane, Maharashtra. He received his Bachelor of Technology degree in information technology from Anna University, Chennai in 2005. Raghav joined the University of Florida to pursue his higher education. In summer 2008, he earned his Master of Science degree in computer engineering. He also earned his Master of Engineering degree in agricultural and biological engineering from the University of Florida in Fall 2009.