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Experimental Evaluation Of Transmission Link Characteristics In Body Area Networks

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EXPERIMENTAL EVALUATION OF TRANSMISSION LINK CHARACTERISTICS IN BODY AREA NETWORKS

by

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EXPERIMENTAL EVALUATION OF TRANSMISSION LINK CHARACTERISTICS IN BODY AREA NETWORKS

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Recent advances in digital electronics, embedded systems, and wireless communications have led the way to a new class of distributed Wireless Sensor Networks (WSNs). A Body Area Network (BAN) is a WSN consisting of miniaturized, low-power, autonomous, wireless biosensors, which are seamlessly placed or implanted in the human body to provide an adaptable and smart health care system. The possible applications of BAN are in health care services and medicine, assisting persons with disabilities, and entertainment and sports.

The nodes in a BAN generally use IEEE 802.15.4 radios which have low-power consumption and are relatively immune to interference. In this thesis, we present the results obtained by performing multiple experiments by placing these sensor nodes on the human body. The focus of our work is to observe how the values for Packet Reception Rate (PRR), Received Signal Strength Indicator (RSSI), changes in distances, and transmission power levels, vary when the experiments are performed off and on the human body. We observe and analyze how these values vary when a single sender node transmits to a single receiver node, and when multiple senders transmit to a single receiver.

The results show that the human body possesses challenges with respect to the communication of sensor nodes. The human body seems to adversely affect the radio propagation and communication such that nodes on some parts of the body may

have limited connectivity to nodes on other parts. We notice that the human body itself, not only affected radio propagation but also led to attenuations in signal levels received by on-body sensors, as a result of which the nodes had varied connectivity between them.

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Chapter 1

Introduction

Advances in hardware and wireless communication technology have led the way to a new class of distributed wireless sensor networks. These networks are made out of nodes which collaborate among themselves to establish a sensing network. Each node is generally made out of a microcontroller, radio transmitter, receiver, and various sensors. Depending on what the node is being used to sense for, the nodes form a network which provide access to information anytime, anywhere by collecting, processing, analyzing, and disseminating data. Sensor networks are used in a variety of applications such as military, environment, health, home, and other commercial areas.

In the following section we discuss more about Wireless Sensor Networks (WSNs), their applications, Body Area Networks (BANs), architecture, applications, and challenges related to BANs and our simulated environment.

1.1 Wireless Sensor Networks

Recent advances in digital electronics, embedded systems, and wireless communications have led the way to a new class of distributed Wireless Sensor Networks

(WSNs) [7]. WSNs can greatly simplify system design and operation because the environment being monitored does not require the communication or energy infrastructure associated with wired networks [9]. Wireless Sensor Networks are composed of wireless devices that cooperatively monitor their surrounding. Wireless communication has given rise to the development of low-cost, low-power, multi-functional sensor nodes which are small and can communicate short distances. These sensor nodes collaborate among themselves to establish a sensing network. Every node often has at least one sensor to measure, for instance temperature, pressure, motion, and power consumption. Since every node communicates wirelessly with other nodes, the nodes can be spread over a large area [17]. Sensor nodes consist of components capable of sensing, data processing, and communication [5].

1.2 Applications

There are many and varied applications for WSNs, but typically involve some kind of monitoring, tracking, and controlling. Sensor network applications can be categorized into military, environment, health, home, and other commercial applications. Many of the sensor network applications are discussed in [5], [8], [24]. Some of them are mentioned below:

1) Military Applications: Sensors are widely used in military applications such as tracking enemies, weapon targeting, monitoring inimical forces, battlefield surveillance, etc.(since they are self-organizing, fault tolerant, and provide rapid access to data and have computing characteristics) [5].

2) Environment Applications: Sensors are used to detect/alert calamities like earthquakes, volcanoes, and tornadoes. Sensors employed with structures, bridges, dams, etc., self-diagnose the problems caused due to earthquakes and report repairs

to be done. Sensor nodes report climatic changes in difficult to reach locations [5].

3) Structure Monitoring: Structure monitoring systems detect, localize, and estimate the extent of damage. Civil engineering structures can be tested for soundness using sensors [8].

4) Healthcare monitoring: Health applications involve tracking patients and monitoring drug administrations in hospitals [5].

- Tele-monitoring of Physical Data: The physiological data collected from sensors can be used for medical exploration. This data can also be stored for a long period of time. The sensor networks detect elderly people's behavior. These small sensor nodes allow the doctors to identify pre-defined symptoms.
- Drug Administration in Hospitals: The chance of getting and prescribing the wrong medication to patients can be minimized if sensor nodes can be attached to medications and patients have sensor nodes that identify their allergies and required medications.

5) Home Applications:

Sensors are envisioned to be ubiquitous, integrating themselves into all household appliances. Such devices are connected to actuators which take an action when the environment changes to a particular state. When outside of the home, users could communicate with these devices making control decisions remotely [24].

1.3 Body Area Networks

Recent Advances in electronics and integrated circuit have led to the development of miniaturized autonomous sensor nodes.

A Body Area Network (BAN) is a WSN consisting of miniaturized, low-power, autonomous, wireless biosensors, which are seamlessly placed on or implanted in the human body in order to provide an adaptable and smart health care system [34].

1.4 Architecture of a BAN

The architecture of a BAN is made up of two main components [26]: multiple body sensor units and a body central unit. The multiple body sensor units mainly consist of two kinds of devices: sensors and actuators. The sensors are used to monitor and measure certain parameters of the human body. The monitoring can either be done externally or internally. Some examples of external monitoring include the measuring of the heartbeat, blood pressure, and body temperature [18]. A few examples of internal measurements are monitoring glucose levels in the blood of diabetics and endoscopy using a sensor integrated pill. The actuators, based on the data received from the sensors, take some specific actions. An example of this is the administration of insulin for diabetics. Hence, the body sensor units perform vital medical data acquisition, pre-processing of data, actuator control, data transmission, and provide some basic user feedback.

The body central unit links multiple sensor units, performs data compression, actuator control, basic event detection/management, and provides external access together with a personalized user interface. Hence, a body sensor unit communicates with a body central unit, which communicates with a person at a remote location.

The communication between the body sensor units and body central unit is called intra-BAN communication. The communication between the body central unit and the person at a remote location is called extra-BAN communication. This kind of communication in a BAN helps to transfer real time data to a person at a remote location, eliminating the use of wires.

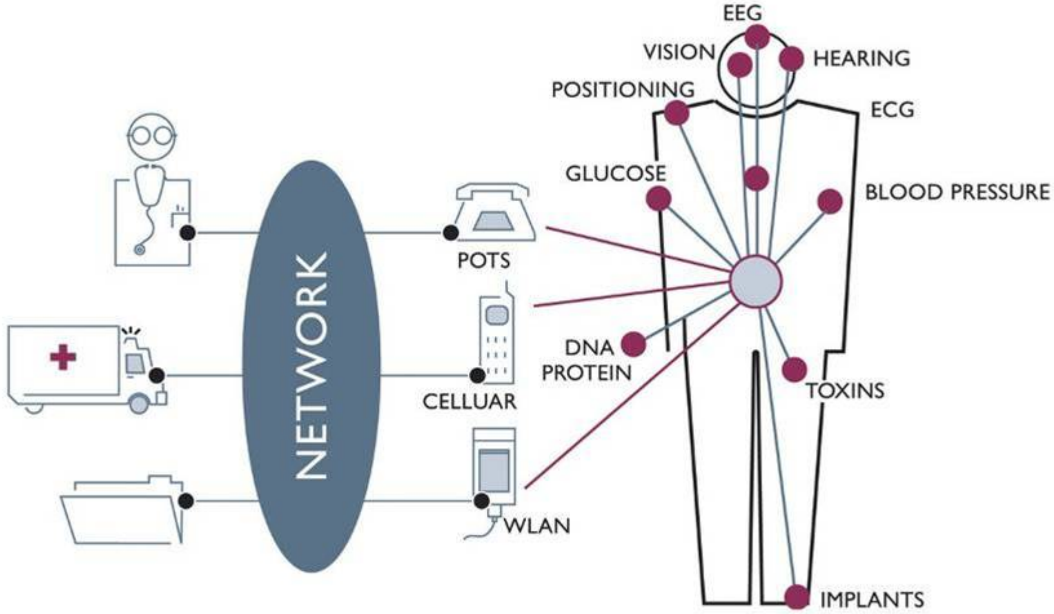


Figure 1.1: Architecture of a BAN [26]

1.5 Applications of BAN

The possible applications of BAN range from simply collecting raw data from a single sensor to highly complex distributed processing algorithms involving many nodes.

BAN applications can be divided into three categories [20] [14]:

1) Health care services and medicine applications. 2) Assisting persons with disabilities applications. 3) Entertainment and Sports applications.

1.5.1 Health care services and medicine applications

A BAN can be utilized to monitor the patient's vital signs (temperature, blood pressure, heart rate, ECG, EEG, respiration rate, etc). No matter whether the patient is in a hospital or at home, BAN provides real time feedback and can be a part of diagnostic procedure, maintenance of chronic condition, supervised recovery from a surgical procedure and to monitor effect of drugs therapy [5].

A BAN can be used to continuously monitor and measure the glucose level in blood and the actuators nodes can administer the appropriate dose of insulin in case there is a sudden drop of glucose [21]. Implants and self moving capsules that have in-body missions can be controlled and may have the possibility to transmit their collected data.

Another application of BAN is in the area of intensive physical therapy [20]. Electronic rehabilitation systems can drastically improve the quality of patient care by providing real time feedback to the patients suffering from injuries or undergoing surgeries. Long term monitoring of patient activities under natural physiological states improves their quality of life by allowing patients to engage in normal daily activities, rather than staying at home or in a hospital. As an example, consider an automatic treatment process [20]. This could be thought of as of having three phases. Phase one consists of the collection of important health care data using the various sensors that are attached to the patient. The data collected is forwarded to a command unit. In phase two, based on the data that is received by the command unit, it decides what treatment method needs to be provided and sends its decision to the action unit. In phase three, the action unit conducts the treatments as per the specification it received. At the end of the third phase all the sensors update the data for a specified amount of time.

1.5.2 Assisting persons with disabilities applications

An application of BAN is fall detection and prevention [21]. Real-time systems that can detect falls can also automatically alert emergency personnel. A fall detection system should require little maintenance and interaction on the user's behalf. To gain widespread adoption, fall detection systems must easily integrate with existing emergency alert systems. A person who is undergoing rehabilitation due to a leg injury can have muscle tension sensors on the injured area. This would help gather data with respect to the injured location. This data would be useful to make a future decision as to whether additional support needs to be provided.

A BAN can also be used in assisting a person with a visual disability [20]. By attaching cameras near the glasses of a person, obstacles such as stairs or vacant seats can be detected. In addition to this, radars attached to a stick of the person can indicate the location or the correct direction. The information provided by the camera and radars can be stored on a portable device that is carried by the person. The processor in the device can interpret this information and can convert it into data/ voice which would help the person in making correct decisions.

In addition to fall detection, elderly monitoring enables early detection of illness, along with prevention of injuries, and helps in ensuring overall well-being. Bodynets should be reconfigurable in real time such that it should be able to interface with sensors in order to offload processing to more powerful devices [12]. In order to carry out this we must make sure that nodes can be easily added and removed according to convenience. Also, elderly people can keep track of their health conditions without frequent visits to their doctor's offices. Meanwhile, their doctors can still access the data and give their patients advice based on these data.

1.5.3 Entertainment and Sports applications

In the fields related to entertainment, wearable BANs can be used to stream audio/visual signals from portable devices to external displays, show pictures, and videos from a digital camera or a camcorder on a television screen. The use of BAN in this area can eliminate the use of wires and increase convenience by source sharing. (e.g. wireless headphones can be used by two persons to share the same music player.)

BAN can also be used in a music store, an art gallery, at the bus stop, or in a car. In the music store, a person can listen to the sample tracks of a music album through his BAN capable headset. At an art gallery, a person can listen to the explanation of a piece of work by clicking on the available button on the BAN interface and the BAN capable headset [14].

In the field of sports, it will be possible to take many different readings from athletes without having them on a treadmill in a laboratory/gym. The ability to measure various levels during real life competition, a race for example, would give coaches a more accurate picture of their athlete's strengths and weaknesses. Wireless sensors can be added as needed to monitor data such as speed, body temperature, and heart rate.

1.6 Challenges

A number of issues and challenges such as interoperability, privacy and security, low-power communication, biosensor design, power consumption, communication link between the implanted device and external monitoring control equipment, needs to be resolved to provide a successful BAN [34].

Some of the challenges are stated below.

1) Node Size:

In order to achieve non-invasive and unobtrusive continuous health monitoring, wireless medical sensors should be lightweight and small. The size and weight of sensors is determined by the size and weight of batteries [15]. Moreover, a battery's capacity is directly proportional to its size. With advances in technology and integrated circuits, it can be expected to have sensors that are small, unobtrusive, ergonomic, and easy to put on.

2) Sensor Type:

What type of sensor should be included in the BAN? This would largely depend on where and for what purpose the sensor would be used. The nodes can be motion position sensors such as accelerometers, health monitoring sensors such as ECG, EMG, or hearing of visual aid and environment sensors such as oxygen, pressure or humidity sensors. Sensors should be flexible with regard to adapting to environment changes [15].

3) Power:

If the BAN is designed to be used for a long period of time then the power sources should be efficient enough and long lasting with minimum or no maintenance. Moreover, low-power consumption is very important so sensors should ideally be self powered, using energy extracted from the environment in the future [15].

4) Interoperability and Customization:

These sensors should configure in such a way that a user can easily assemble them and should be easily customizable [33]. The BAN sensors must be able to work in different kinds of environments. BAN needs to co-exist with other BANs, legacy networks/devices, and electronic health record systems.

5) Communication Range:

This depends on the area where the person is going to be. Is the area a hospital, home or a battleground, in the case of a soldier. Standards should be followed for wireless communication, messaging and system support.

6) Safety, Reliability, Security, and Privacy [33]:

Wireless medical sensors must meet privacy requirements and must guarantee data integrity. They should be fault tolerant.

Security measures such as user authentication should prevent unauthorized access or manipulation of functioning of the system.

Privacy means that when data is required to be transmitted over the internet, to protect user privacy, it is required to be encrypted. In addition to this, the physician at the remote place who is monitoring or analyzing the data should identify himself before he has access to private data.

1.7 Simulation Environment:Tiny Microthreading Operating System(TinyOS)

TinyOS [19] is an open source operating system designed for wireless embedded sensor networks. It aims at supporting sensor network applications on resource constrained hardware platforms.

TinyOS uses an event-driven concurrency model and utilizes a component-based architecture. TinyOS provides an efficient framework that allows the OS to adapt to hardware diversity while still allowing applications to reuse common software services and abstractions.

A TinyOS application normally consists of a number of components wired together. Each component may use other components. Higher level components issue commands to lower level components and lower level components signal higher level components. The program execution is rooted in hardware events and tasks. Hardware events are interrupts, caused by a timer, sensor, or communication device. Tasks are a form of deferred procedure call that allows a hardware event or task to postpone processing. Tasks are posted to a queue. As tasks are processed, interrupts can trigger hardware events that preempt tasks. When the task queue is empty, the system goes into a sleep state until the next interrupt. If this interrupt queues a task, TinyOS pulls it off the queue and runs it. If not, it returns to sleep. Tasks are atomic with respect to each other.

1.8 nesC - Network Embedded System C

nesC [11] is an extension of C. Applications written in nesC that run on wireless sensor motes are built by writing and assembling different components as required. The interfaces are the only point of access to the component and they are also bidirectional: they contain commands and events. Commands and events are mechanisms for inter-component communication. A command is typically a request to a component to perform some service, such as initiating a sensor reading, while an event signals the completion of that service. Events may also be signaled asynchronously, for example, due to hardware interrupts or message arrival. All nesC applications have a top level configuration which connects all the components used. Modules are components that provide an implementation of commands for the interfaces and events for the interfaces it uses.

1.9 Hardware

The sensor network hardware platforms usually consist of three components:

1.10 MicaZ motes

In our experiments we have used Berkeley MicaZ motes, manufactured by Crossbow Technology [3]. This is an open-source hardware and software platform that combines sensing, communications, and computing into a complete architecture. Micaz, being a third generation platform, has a higher data rate radio, which is IEEE 802.15.4

Figure 1.2: MicaZ Mote

compliant.

The MicaZ sensor hardware platform has an 8-bit 8 MHz Atmel ATmega128L microcontroller (128 kB ROM and 4 kB RAM) and a Chipcon CC2420 radio, and is powered by 2 AA batteries. It also has a detachable, quarter wave, monopole antenna connected to an MMCX jack on the MicaZ circuit board and a 51-pin expansion connector for light, temperature, barometric, acoustic, magnetic and other Crossbow sensor boards.

1.11 CC2420 radio transceiver

The CC2420 radio transceiver [1] in the MicaZ platform is a single-chip 2.4GHz band transceiver that is IEEE 802.15.4 compliant, designed for low-power and low-voltage wireless applications. CC2420 includes a digital direct sequence spread spectrum baseband modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps.

The CC2420 provides information about received packets. The first is its received signal strength indicator (RSSI), which is the strength in dBm of the RF signal received over the first eight symbols after the start of a packet frame. The second is the link quality indicator (LQI), which is an unsigned integer in the range of 50 to 110. The CC2420 calculates the LQI over the first eight symbols of each incoming packet.

RF transmission power is programmable from 0 dBm to -25 dBm. Typically, the CC2420 consumes the current of 18.8 mA in the transmit mode and that of 17.4 mA in the receive mode and have a typical sensitivity of -95 dBm.

1.12 MIB520 USB Interface board

The MIB520 shown in Figure 1.3 is a multi-purpose USB interface board that provides USB connectivity to the Mica family of motes for communication and in-system programming [2]. The MIB 520 has an on-board in-system processor (ISP), an ATmega16L to program the motes. Code is downloaded from a PC to the ISP through the USB port. Next the ISP programs the code into the mote.

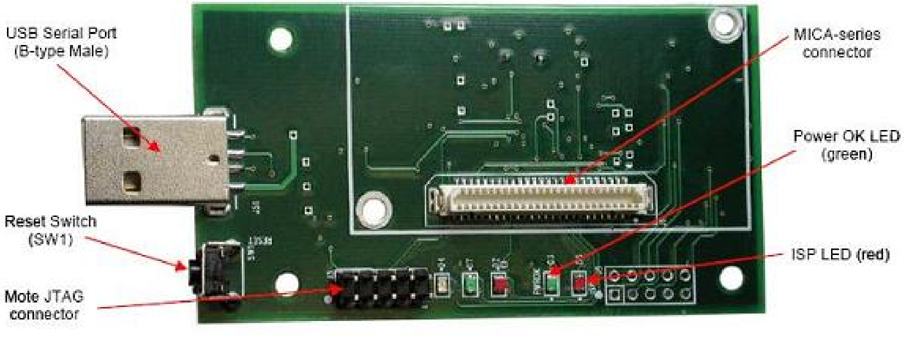


Figure 1.3: Photo of top view of an MIB520 [4]

The mote which is attached to the MICA-series connector of the MIB520 is defined as the base station. It allows the aggregation of sensor network data onto a PC. Any MicaZ mote can function as a base station when it is connected to the

MIB520. Therefore, the MIB520 provides a fundamental serial/USB interface for both programming and data communications for any WSN.

The rest of this thesis is organized as follows. Link estimation metrics, background and work related to link characteristics in WSN's and BAN's are outlined in Chapter 2. Chapter 3 describes our research problem, the objectives of this research, and our approach. Chapter 4 describes our experimental setup, how we evaluated our setup and presents the results. Finally, chapter 5 concludes this thesis and describes future work.

Chapter 2

Background and Related Work

An application of WSN is in remote health care monitoring of patients. A few of the health applications for sensor networks are providing integrated patient monitoring diagnostics, drug administration in hospitals, telemonitoring of human physiological data, and tracking of patients and doctors inside a hospital [5]. In the past, wired biosensor networks were used which not only limited the movement of users by the way in which they were interconnected, but also involved high maintenance costs. A wireless connection is not as reliable and stable compared to a wired connection. There are a number of factors which can affect a wireless connection network.

A Body Area Network (BAN) is an area of research for WSN wherein the sensor nodes are used to gather different kinds of medical data from different parts of the human body. The nodes in a BAN generally use IEEE 802.15.4 radios which have a relatively low power consumption and are relatively immune to interference. The human body seems to affect the wireless connection link qualities, as well as the radio propagation between the nodes placed on different parts of the body. Here we have performed some experiments by attaching various sensor nodes to the human body and observed the results with regard to Packet Reception Rate (PRR), RSSI

(Received Signal Strength Indicator), distance, power transmission levels, and changes in frequency.

Formerly, a lot of work has been done with regard to link characteristics. But most of these were performed in either outdoor environments like potato fields and open parking lots or indoors in an office building. In the following sections we discuss the link estimation metrics and related work done over the past few years.

2.1 Link Estimation Metrics

1) Packet Reception Rate (PRR)

Packet Reception Rate (PRR) is one of the techniques used to determine the link quality. PRR is the ratio of the number of successful packets to the total number of packets transmitted over a certain duration [25]. Higher PRR value means that more packets can be received and thus the link quality is better. In some links, the probability that a packet will be dropped is independent of the success rate of the packets that are sent before and after said packet. However, there are situations where the errors are more likely to occur in bursts. These groups of errors usually prove to be more detrimental in networks versus the cases where the errors are independent and uniformly distributed.

2) Received Signaled Strength Indicator (RSSI)

Receive Signal Strength Indicator measures the strength of an incoming signal [25]. It is designed to pick RF signals and generate an output equivalent to the signal strength. The ability of the receiver to pick the weakest of signals is referred to as receiver sensitivity. The higher the receiver sensitivity, the better is the link quality. There are circuits which measure the signal strength based on the output voltage. RSSI value is an integer range from -100dBm to 0dBm for CC2420 radio.

3) Sequence numbers

By means of sequence numbers it is possible to trace lost packets in a packet stream, which allows to evaluate if there are bursts or striking patterns of packet losses.

2.2 Related Work

Thelan, Goense and Langendoen [32] conducted a research study wherein Mica2 motes were planted into a potato field and measurements of Receive Signal Strength (RSS), Packet Reception Rate (PRR) and distance were taken. The research explored the relationship betweeen PRR and RSS and that of RSS with distance. Numerous nodes were planted in the field and the RSS was measured in different weather and environmental conditions. The results showed that with an RSS of at least -90dBm, a 73 percent packet reception rate is achievable. When the RSSI is below -90dBm, the packet reception rate became totally unpredictable.

Ganesan et al [10] conducted experiments on packet delivery for Rene motes, an early-generation sensor node, and analyzed different protocol layers, showing that even simple algorithms such as flooding had significant complexity at large scales. They observed that many node pairs had asymmetric packet reception rates and attributed this to receiver sensitivity differences.

One of the first attempts of systematic measurements of packet delivery in wireless sensor networks had been performed by Zhao et al. [36] in 2003. They placed Mica nodes in a simple linear topology in three different environments: an indoor office building, a habitat with moderate foliage and an open parking lot. Based on their measurements, they divided the communication range of the node in three regions: a region close to the sender in which all nodes received most of the packets, a region out of range, and the gray area in between. The region at the edge of the communication range in which the reception rate varied dramatically; had some nodes show nearly 90% successful reception, while neighboring nodes sometimes had less than 50% reception rate. Against their expectations, this area had a significant variation. While the gray area, measured on the parking lot, coverd 10% of the total communication range, it coverd 30% of the measurements in a habitat and 50% of the measurements in the office building. They referred their findings to multi-path signal delivery. Moreover, they found significant asymmetry in realistic environments but were not able to establish causes for their findings.

Woo et al. [35] measured signal strengths in a uniform grid over a large, essentially unobstructed indoor space with 50 nodes (Mica). The results showed that both, the mean link quality, and the variance in quality are a function of distance. They determined three different regions: the effective region where the reception rate is above 90%, the transitional region where some of the links are good and others are not, and the clear region where no more packets can be received. The borders of these regions lie at about 10 and 40 feet, respectively. These findings are comparable to the gray area defined by Zhao et al. [36]. Furthermore, they confirmed the existence of asymmetric connectivity. All of these studies measured early mote platforms (e.g. Rene, Mica, and Mica2), and we survey the packet delivery performance regarding MicaZ sensor platforms below.

Srinivasan et al [30] showed empirical measurements of the packet delivery performance for MicaZ motes. They observed that RSSI was quite stable over a short period of time, thus being a good predictor of short-term link quality, and RSSI above the sensitivity threshold corresponded to a high PRR. In the meantime, they found that LQI varied over a wider range over time for a given link, but the mean LQI computed over many packets had a better correlation with PRR. They also observed that while short-term link asymmetries are not uncommon, long-term asymmetries are rare.

A number of studies have discussed interference caused by the human body and differing environments on radio communications. Kara et al [16] showed the effect of people crossing a link between a transmitter and a receiver operating at 2.4 GHz. They use a customized RF transmitter that generates signals with a power of 20 dB. The shadowing effect caused by a human body crossing the line of sight (LoS) links between a transmitter and receiver for transmissions have been discussed in [23]. The degradation of the radio signal when passing through the human body is described in [27]. The indoors and outdoors evaluation of 802.15.4 radio for static sensing platforms through a characterization of the Radio Signal Strength Indicator (RSSI) for different transmitter-receiver distances has been discussed in [30] [6]. In [6] [29] , the authors state that the antenna orientation greatly impacts the RSSI and the incidence of the asymmetric links.

Jea and Srivastava [13] presented some results on connectivity in a body area network using the mica2dot motes. Their results suggested good connectivity among all nodes on a body beyond a certain transmit power. They used packet reception rate as a metric for wireless communication performance. The factors that they explored in the experiments were the relationships between RF transmission power values by placing nodes on different parts of the body. They considered two scenarios of standing and walking. They also conducted experiments with different setups for the antennas (built-in, removed and flat circle).

Natarajan et al. [22] identified design goals and evaluated them against the star and multi-hop network toplogies. The authors examined the performance of IEEE 802.15.4 through and around the human body using network layer metrics such as packet delivery ratio and latency. They observed that the human body is similar to aluminium in that it has a very good RF shield, such that no packet can get through without multipath. They developed a novel visualization tool which provided a way to discern patterns in large datasets visually. In addition to this they suggested that a star topology operating at low power levels might suffice in an indoor environment, whereas in an outdoor environment, nodes would have to operate at higher power levels.

Ren et al. [25] conducted experiments to observe how the quality of sensors are affected by surrounding factors. Varying the postures of the body, they performed experiments varying the power level in different environments. They placed a single sensor on the left arm and varied the distance from the receiver and examined the correlations between packet reception rates, distance and transmission power.

Shah et al. [28] conducted experiments on multiple people to measure the effect of human body on the performance of Bluetooth and IEEE 802.15.4. They considered different locations on the body such as the ankle, ear, knee and chest, while assuming the location of the on-body aggregrator as the waist. They allowed mobility of the human, while measuring the effect of IEEE 802.15.4 and Bluetooth. In the end they explored the co-existence of both the radios.

Shah and Yarvis [29] examined the characteristics of the links in and on-body IEEE 802.15.4 network and the factors that influence link performance. They used Intel Mote 2 devices and placed them on three areas: the chest, the right side of the waist and the right ankle, while setting the transmit power of the radio at 0dBm. They observed that the wireless links among nodes in an on-body IEEE 802.15.4 network are not as benign as expected. While 802.15.4 radios typically have a range of at least 10 meters in most indoor environments, when placed on a body, the range seems to be less than a meter.

Chapter 3

Research Problem and Objectives

This chapter gives us information about the research problem, our approach about how to solve this problem and the objectives of this research.

3.1 Research Problem

A Body Area Network(BAN) is a WSN consisting of miniaturized, low-power, autonomous, wireless biosensors, which are seamlessly placed on or implanted in the human body in order to provide an adaptable and smart healthcare system.

A wired connection generally restricts the movement of an individual and also involves high maintenance cost. A wireless network on the other hand removes the limitations but has its own set of issues and challenges. Issues such as interoperability, low-power communication, biosensor design, power consumption, communication between the implanted device and external monitoring and control equipment, surrounding environment and actions of a human being needs to be resolved to provide a successful wireless system.

In order for a BAN to operate in the way it should, it is important to ensure that the communication between the various sensor nodes takes place in the desired manner. The human body possesses challenges with respect to the communication of sensor nodes placed. The human body seems to adversely affect the radio propagation and communication such that nodes on some parts of the body may have little or no connectivity to nodes on other parts.

The goal of this thesis is to study how the human body affects wireless link quality metrics when different sensor nodes are attached on it. The packet reception rate (PRR), received signal strength indicator (RSSI), distances and transmission power are used as metrics for wireless communication performance.

3.2 Methodology

In order to find out how the human body affects wireless link qualities, we carried out different experiments. To determine the relationship between various performance metrics, we performed multiple experiments consisting of different scenarios. In all our experiments we have used Berkeley MicaZ motes, manufactured by Crossbow technology. In addition to this we used a CC2420 radio transceiver, which is a single-chip 2.4GHz band transceiver and IEEE 802.15.4 compliant, designed for low-power and low-voltage wireless applications.

The experiments which we performed are described briefly below:

In the first experiment, we used two MicaZ nodes. These two nodes were placed on a table. One of them acted as a base station to receive values from the other node. We made sure that there existed a clear line of sight between the transmitter and the receiver. We varied the distance and transmission power values to observe the PRR and RSSI values.

In the second experiment, one MicaZ node was placed on the right arm, and we varied the distance and transmission power, between the transmitter and receiver.

In the third experiment, we used six MicaZ nodes and placed them on two parallel sticks. Each of the nodes transmitted packets to the remaining nodes, while varying the power levels. Three transmission power levels (-25 dBm, -15 dBm, and -10 dBm) were used during this experiment.

In the fourth experiment, we used the same setup as the previous experiment, but instead of using the sticks we placed the sensor nodes on the human body. These six MicaZ nodes were placed on different parts of the human body. Each of them transmitted packets to the remaining nodes. Three transmission power levels were used during this experiment.

In the fifth experiment, based on the setup of experiment four, we allowed two nodes to simultaneously transmit packets to each of the remaining nodes. We repeated the experiment using three and five senders.

For each of the scenarios explained above, we performed multiple trials with varied transmission power levels. Based on the results that we collected, we plotted graphs which showed the relationship between PRR and RSSI with respect to transmission power level and distances.

3.3 Research Objectives

Our research consisted of the following objectives:

- To study how the human body affects the connectivity between various nodes placed on different parts of the body.
- To understand how the communication link behaves by monitoring the packet reception rate and the received signal strength intensity values.
- To analyze the results that occurred when a single transmitter transmits to a

single receiver under three different transmission power levels.

- To analyze the results that occurred when two nodes act as senders and transmits to a single receiver under three different transmission power levels.
- To observe whether the placement of nodes affects the connectivity between the nodes placed on different parts of the human body.

Chapter 4

Experimental results and analysis

This chapter has been divided into two main sections. The first section, 4.1 explains how the systems are setup in order to carry out the experiments. The second section, 4.2 describes the results and graphs plotted, along with the analysis.

4.1 Experiment Setup

In all our experiments we have used Berkeley MicaZ motes, manufactured by Crossbow technology. We have used a CC2420 radio transceiver, which is a single-chip 2.4GHz band transceiver and IEEE 802.15.4 compliant, designed for low-power and low-voltage wireless applications. In the experiments three transmission power levels (-25 dBm, -15 dBm, and -10 dBm) were used. For each set of power levels, the PRR and RSSI values were obtained. The transmitter would transmit packets at a data rate of 1 packet per second for ten minutes.

- Experiment Setup 1

  For the first set of experiments we used two MicaZ motes. One of them acted as the base station which recorded the number of packets and the RSSI that it received from the other node. Both the nodes were placed on a table with a clear line of sight between them. The distances which were used were 1,2,3,4,5 and 10 feet. We repeated the experiment for each transmission power level. The physical layout for this experiment is shown in Figure 4.1.

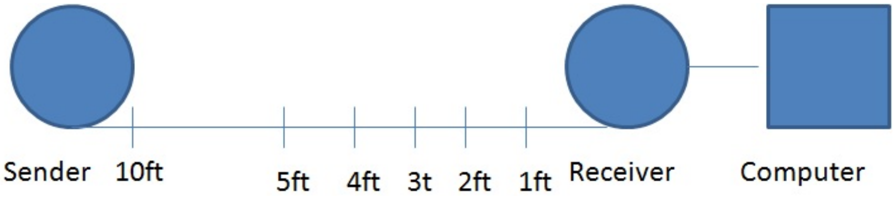


Figure 4.1: Experiment 1 Setup

- Experiment Setup 2

  For the second set of experiments, a MICAz node was placed on the right arm of a human body with distances of 1,2,3,4,5, and 10 feet from the receiver, which was placed on the table.

- Experiment Setup 3

  For the third set of experiments, we made use of two sticks. A node was setup as a base station by connecting it via a USB to the computer. This node received commands from the computer which where sent through radio to the nodes placed on the sticks . We placed the two sticks parallel to each other, with a foot's distance between them. We positioned three MICAz nodes on each stick, such that one was placed at the lower end, one in the middle and one at the upper end of each stick. Node 1 and Node 2 were placed at the lower ends of each stick, Node 3 and Node 4 in the middle and Node 5 and Node 6 at the upper ends. The distance between Node 1 and Node 2, from Node 3 and Node 4 was 4 feet. The distance between Node 3 and Node 4, from Node 5 and Node 6 was 1 foot. We then conducted experiments in such a manner that each node transmitted to every other node. The purpose of performing this experiment was to observe the PRR and RSSI values obtained, when experiments were not performed on body. The setup for this experiment is shown in Figure 4.2

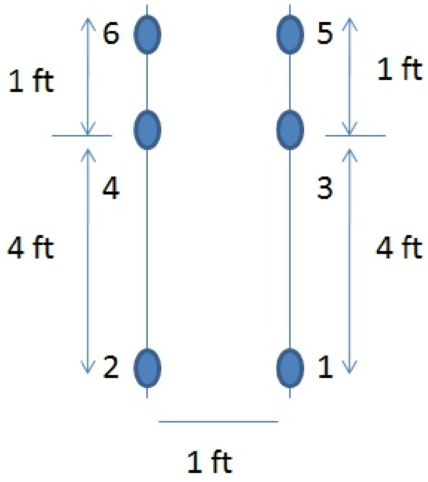


Figure 4.2: Experiment 3 Setup

- Experiment Setup 4

  Experiment 4 was modeled on the previous experiment, the only difference being that, the nodes were placed on the human body. In this experiment we placed six nodes on the human body. We placed the nodes on the left ankle, the right ankle, the left waist, the right waist, the left arm, and the right arm respectively. We then conducted experiments in such a manner that each node transmitted to every other node. For e.g. the right ankle, the left waist, the right waist , the left arm and the right arm nodes would transmit packets to the left ankle one after the other respectively. This process was repeated for each node. The goal of this experiment was to observe how the PRR and RSSI values differed from those of experiment 3.

- Experiment Setup 5

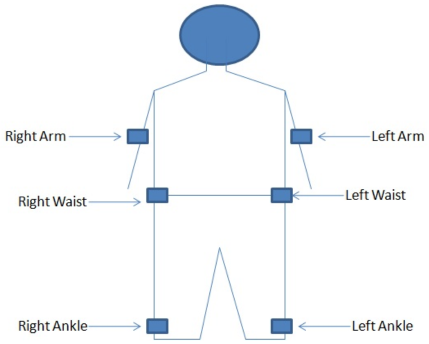


Figure 4.3: Experiment 4 Setup

For the fifth set of experiments, we used the same setup as described in Experiment 4. In this experiment we explored the effect of multiple senders transmitting to a single receiver. The experiments were conducted such that initially two nodes acted as transmitters and simultaneously transmitted to each of the remaining nodes. Further, we increased the number of transmitters to three and five. For e.g. initially the left waist and the right waist acted as the transmitters and simultaneously transmitted, to the left ankle, right ankle, left arm and right arm respectively.

4.2 Results

In this section, the results obtained by performing each experiment are presented. Each test was performed multiple times and the tables in the Appendix show the average values of the results for each experiment. Based on those values we plotted graphs for each experiment. Below we present the graphs for Experiment 1 and Experiment 2 together, followed by Experiment 3, and later on Experiment 4 and Experiment 5.

4.2.1 Results of Experiment 1 and Experiment 2

Figure 4.4 shows the results for experiments 1 and 2 described in section 4.1. Figure 4.4 plots the PRR against the distance for three transmission power levels. The graph indicates there exists a linear correlation between PRR and distance. As the distance between the two nodes increases, the PRR value decreases. We observe that the curves for experiment 1 have a higher PRR as compared to those of experiment 2, for the same transmit power value. The reason for this is the clear line of sight between the nodes placed on the table. In contrast, for experiment 2 the signal propagates through the user which results in lower PRR values.

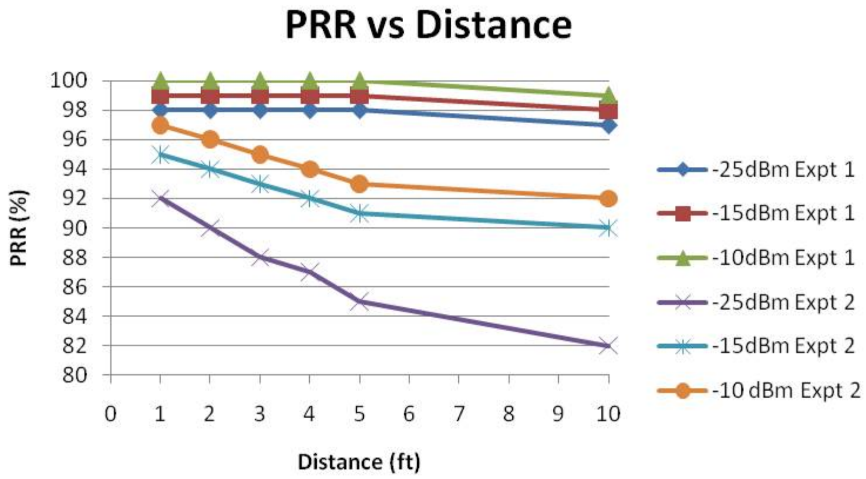


Figure 4.4: Experiment 1 and 2 results: PRR vs Distance

Figure 4.5 shows the RSSI values for each power level as the distance between the two nodes is increased for experiment 1 and 2. The graphs are generated based on the experimental data given in Table 5.2 and Table 5.4 (Appendix). Figure 4.5 indicates that as the distance between the nodes increases, the RSSI values decreases for a given transmission power level. For instance, in experiment 2 at a transmission power level of -10 dBm we get a RSSI value of -83 dBm for 10 ft and a value of -54 dBm for 3 ft. Similarly, for a transmission power level of -25 dBm we get a RSSI value of -92 dBm for 10 ft and a value of -74 dBm for 3 ft. This can be attributed to the fact that the signal attenuates in air over distance.

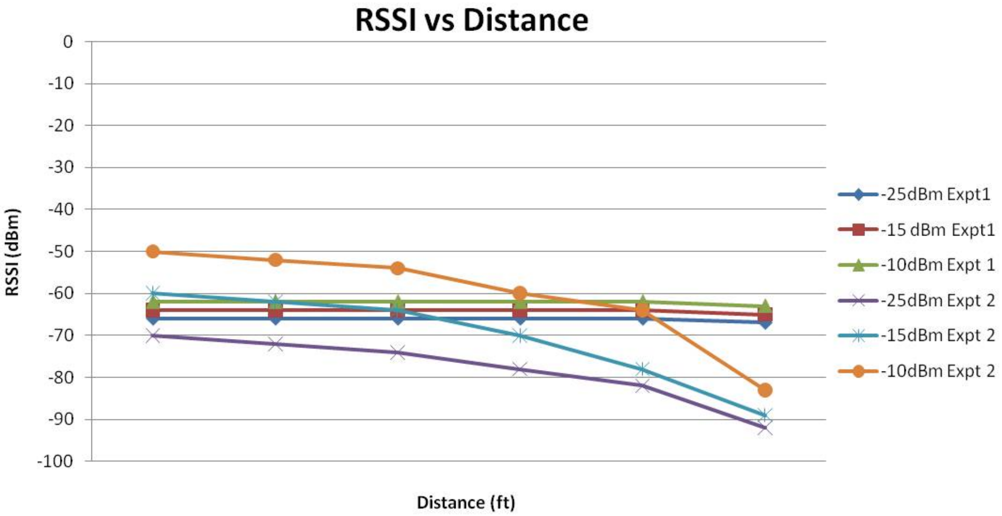


Figure 4.5: Experiment 1 and 2 results: RSSI vs Distance

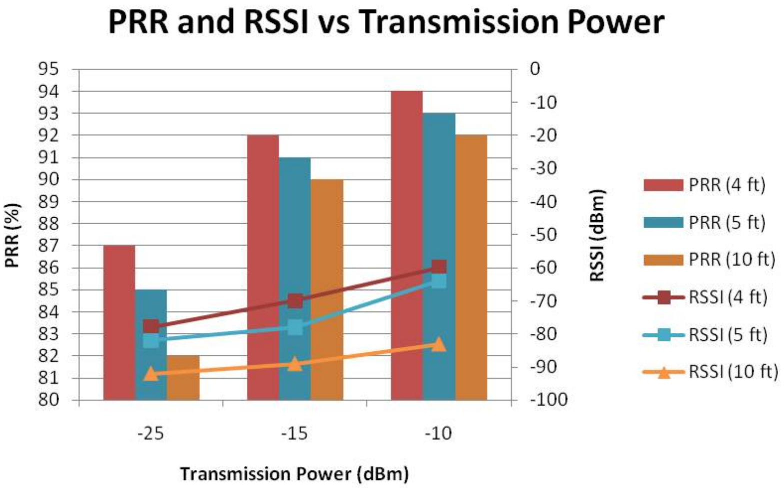


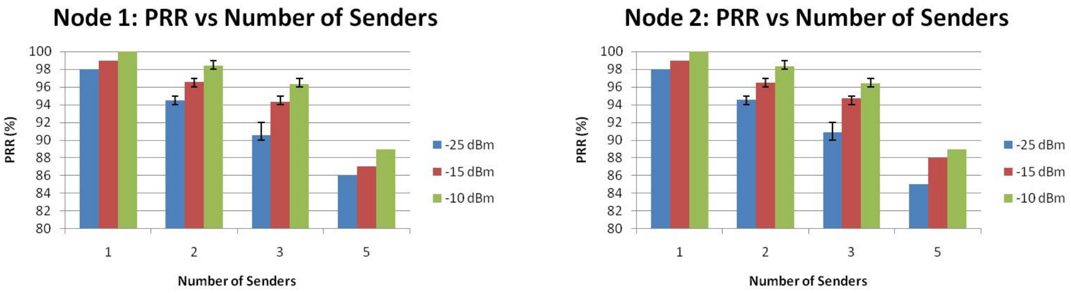
Figure 4.6: PRR and RSSI against Transmission Power Level

PRR is the most direct metric for link quality. However, PRR alone is not enough to show how good the communication link is. Hence, we found the relation of PRR with RSSI. [31] showed that when RSSI is above the sensitivity threshold (about -87dBm), the PRR is atleast 95%, indicating a very good link. Figure 4.6 shows the plot for PRR and RSSI when the distance between the transmitter and receiver is 4 ft, 5 ft and 10 ft. From the graphs plotted, when the power level is above -15 dBm and the transmitter and the receiver is separated by 5 feet or more, the PRR and RSSI value are higher than 90% and -85dBm respectively. This indicates that high PRR values are seen since -85 dBm is close to the sensitivity threshold value of CC2420.

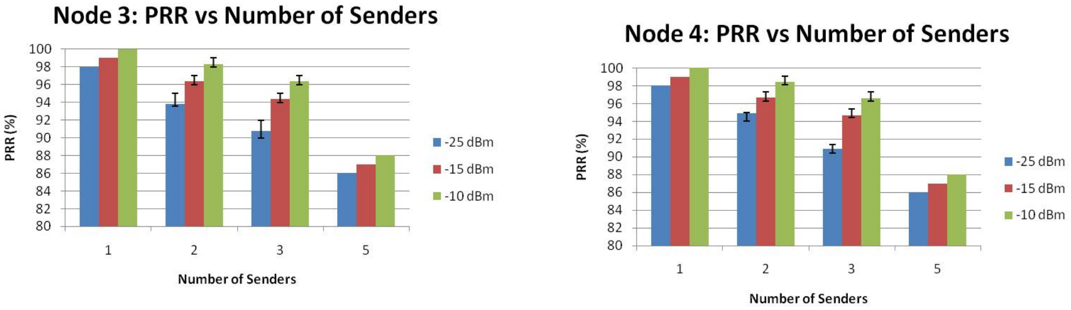
4.2.2 Results of Experiment 3

Based on the experiment 3 setup as described in section 4.1, we obtained results as shown in Figure 4.7. The graphs plotted in Figure 4.7 shows the PRR values against the Number of senders. From the graphs we see that, when there is a single sender and a single receiver, the PRR values seem to be stable. At -25 dBm we get a PRR value of 98%, at -15 dBm we get a PRR value of 99%, and at -10 dBm we get a PRR value of 100%. This could be attributed to the fact that the communication that takes place has less interference. However, on increasing the number of senders, we notice a decrease in the PRR values. The variance in the number of packets received is shows by the error bars in the graphs. We see that when the number of senders are 3 and transmission power level is set to -25dBm, the variance is greater.

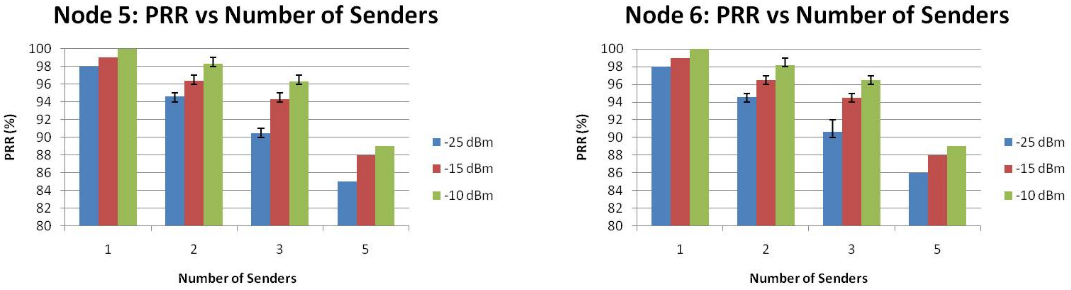
The RSSI values obtained are plotted against the Number of Senders and presented in Figure 4.8. We plot the minimum and maximum RSSI values for each transmission power level as error bars. We observe that as the transmission power level increases, RSSI values decreases. In the next section, we explain more about this when we talk about the RSSI values received from the on-body experiments.



(a) Node 1 (b) Node 2

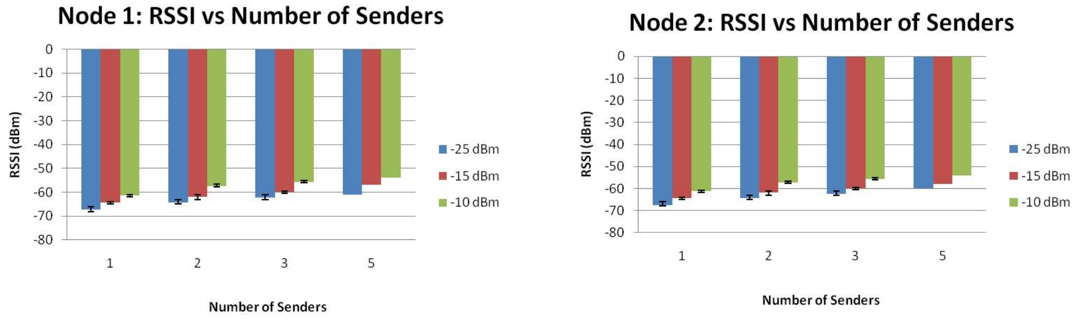


(c) Node 3 (d) Node 4

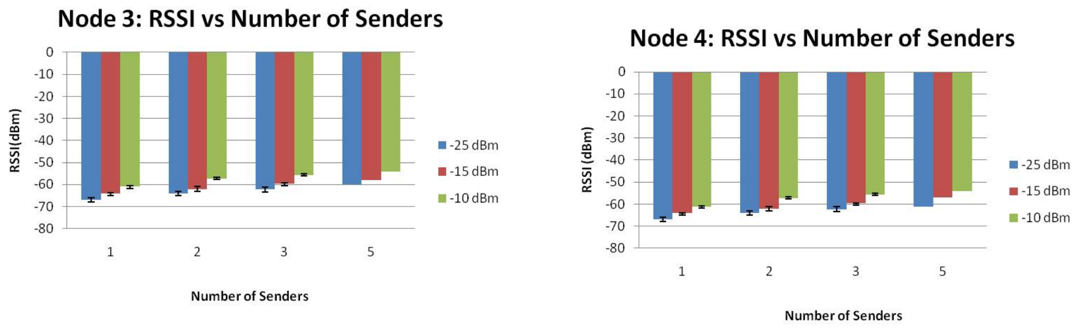


(e) Node 5 (f) Node 6

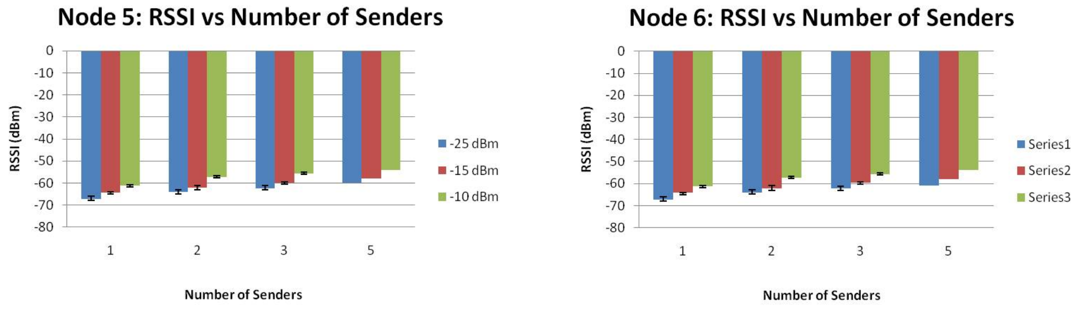
Figure 4.7: Experiment 3 Results: PRR vs Number of Senders



(a) Node 1 (b) Node 2



(c) Node 3 (d) Node 4



(e) Node 5 (f) Node 6

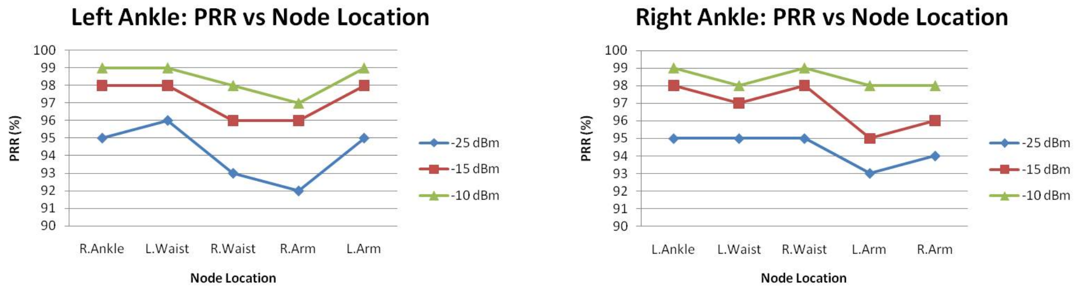
Figure 4.8: Experiment 3 Results: RSSI vs Number of Senders

4.2.3 Results of Experiment 4 and Experiment 5

After performing the experiments on two parallel sticks as mentioned in Experiment 3, we performed the experiments on the human body. We placed the nodes on the human body based on the experiment setups as described in section 4.1. We obtained the values as shown in table 5.17-5.22, and generated graphs as shown in Figure 4.9. Figure 4.9 shows the plots of PRR for a specific receiver against the sender node location. The figure reveals that as the transmission power increases, the PRR value also increases. In addition, we found out that, PRR values for nodes located on the same side of the body are higher as compared to nodes located on opposite sides.

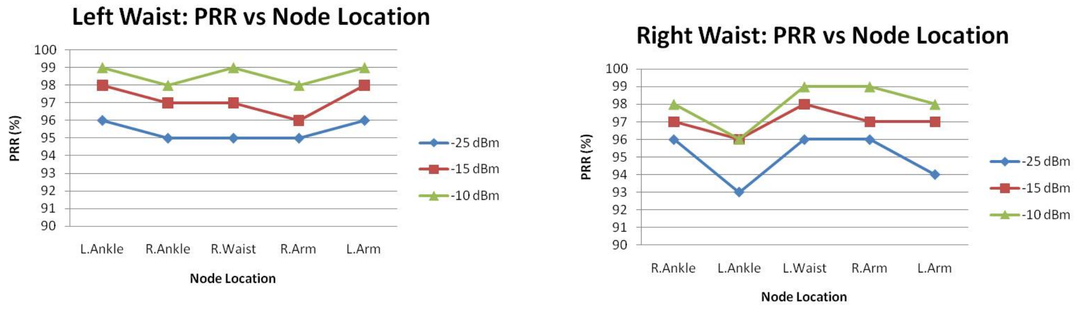
Consider Figure 4.9(a), the graph shows the PRR values for the left ankle at each transmission power level for different sender node locations. At -25dBm, the PRR values are 96 and 95 when the left waist and left arm are the sender nodes, while the PRR values are 93 and 92 when right waist and right arm are sender nodes. Similarly at -10 dBm, the PRR values are 99 when left waist and left arm individually are the sender nodes, while the PRR values are 98 and 97 when the right waist and right arm are senders nodes. This can be explained by the fact that the body acts as a barrier. The human body blocks the transmission between the nodes located on the left side and right side of the body. Thus, communication takes place better between nodes on the same side.

We noticed that the location where the node is located on the human body significantly affect connectivity. The human body seemed to affect radio propagation such that nodes on some parts of the body may have a higher or lower PRR value to nodes on other parts. For instance, the connectivity between the left ankle and the left waist is 96%, while the PRR value is 95% between the left ankle and the left arm. From Figure 4.9 we see that the connectivity between the right arm and the right waist is 96%, while its 94% between the right waist and right ankle. A possible


Left Ankle: PRR vs Node Location

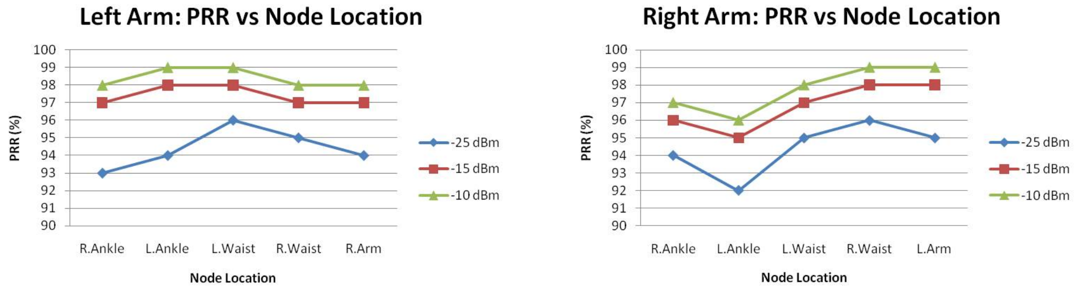
Right Ankle: PRR vs Node Location

(a) **Left Ankle** (b) **Right Ankle**


Left Waist: PRR vs Node Location

Right Waist: PRR vs Node Location

(c) **Left Waist** (d) **Right Waist**


Left Arm: PRR vs Node Location

Right Arm: PRR vs Node Location

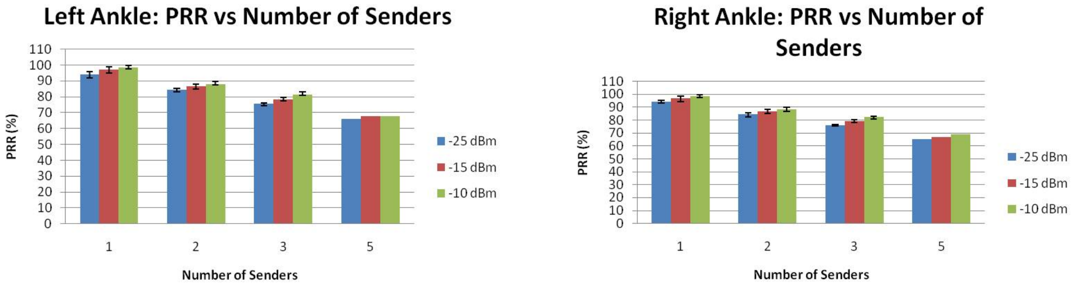
(e) **Left Arm** (f) **Right Arm**

Figure 4.9: Experiment 4 Results: PRR vs Number of Senders at -25dBm

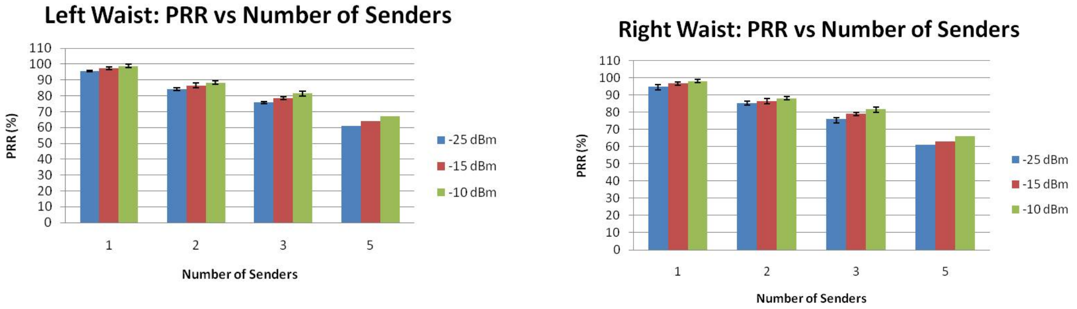
explanation for this could be that nodes with a lower operating frequency of 433MHz radios could permeate better through the human body as compared to 2.4GHz radios.

Furthermore, from Figure 4.10 we see that as the number of senders increases, the PRR values decreases. For example, the values at the transmission power level of -25 dBm for the left waist are 95.4, 84.4 and, 75.8 for 1, 2 and 3 senders respectively. The reason for this is that as the number of senders increases the level of interference between the three senders increases. When multiple senders simultaneously compete for the same channel it leads to dropping of packets.

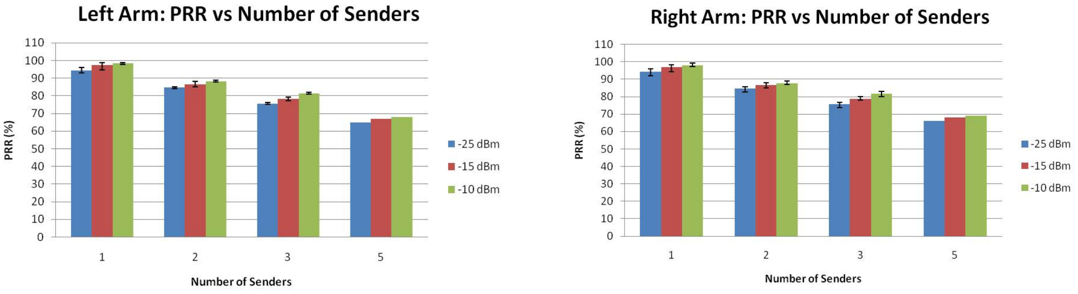
Figure 4.11 shows the average RSSI values and the corresponding maximum and minimum values (as error bars) at each of the three power transmission levels, when the number of senders are varied. Comparing these to Figure 4.8, we notice that the average RSSI values obtained in Experiment 3 are higher. The primary reason for this pattern is because, the nodes present need to cope with the radio transmission around the human body. The human body attenuates radio wave transmission at 2.4 GHz, while the nodes placed on the sticks don't seem be be influenced. We observe that the RSSI values increase smoothly with the transmission power level. At a transmission power level of -25 dBm, we get a RSSI values of -75.8 dBm and at a transmission power level for -10 dBm we get a value of -65.2 dBm, when there is a single sender. On increasing the number of senders to 3, we get RSSI values of -68.8 dBm and -57.8 dBm at -25 dBm and -10 dBm transmission power levels. From the error bars we see that the RSSI values seem to be stable for a specific transmit power level, making RSSI to be a good indicator of channel quality. This could be attributed to the fact that RSSI values are largely influenced by the environments. The relationship and the degree of variation depends on the environment and hence may change overtime.



(a)**Left Ankle** (b)**Right Ankle**

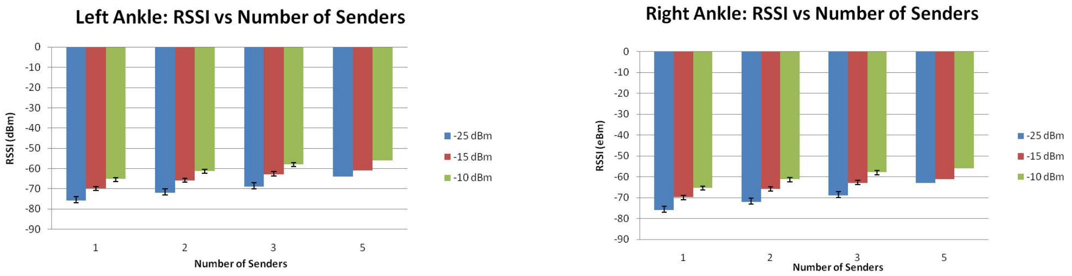


(c) **Left Ankle** (d) **Right Waist**

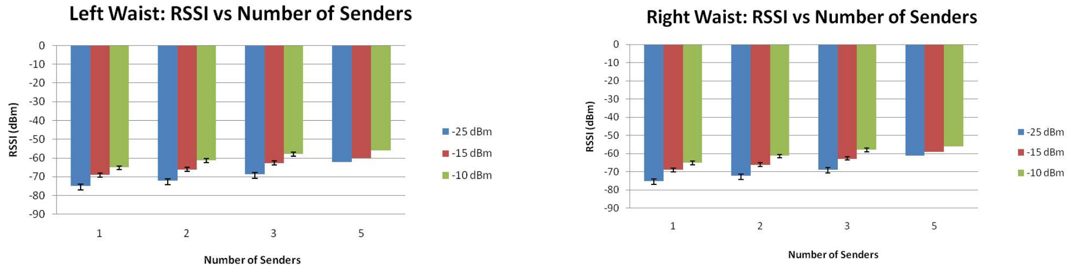


(e) **Left Arm** (f) **Right Arm**

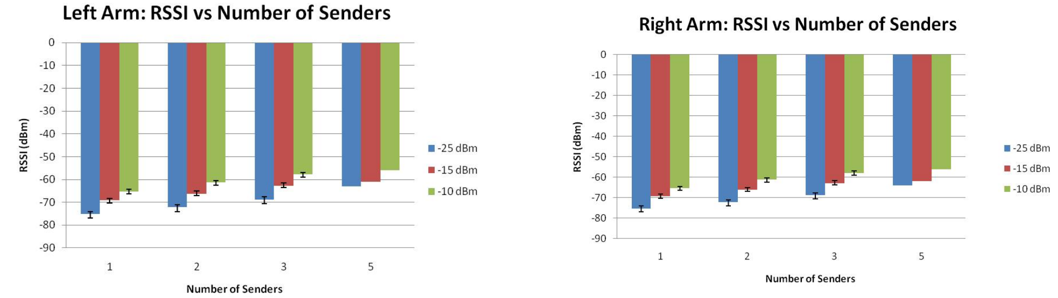
Figure 4.10: Experiment 4 and 5 Results: PRR vs Number of Senders



(a) **Left Ankle** (b) **Right Ankle**



(c) **Left Waist** (d) **Right Waist**



(e) **Left Arm** (f) **Right Arm**

Figure 4.11: Experiment 4 and 5 Results: RSSI vs Number of Senders

Chapter 5

Conclusions and Future Work

In this thesis we have examined how the human body affects wireless link communication by attaching MicaZ sensor nodes onto different parts of the human body. In this chapter we highlight our main contributions and present our future work.

5.1 Conclusions

- We observed that many factors influenced link communication such as PRR, RSSI, transmisssion power levels and distance. Based on the experiments performed by placing nodes on the table, we observed high stable values for PRR and RSSI. The reason for this was the clear line of sight between the two nodes placed on the table. However on placing one node on the human body, we observed different values. As the distance between the two nodes increased, the PRR value decreased. The reason for this was the signal propagated through the user which resulted in lower PRR values. For a given transmission power level, as the distance between two nodes increased the RSSI values decreased. This was attributed to the fact that the signal attenuated in air over distance.

- Initially we performed experiments by placing nodes on two parallel sticks. We compared the values obtained and determined how these differed from the human body experiments. Based on the experiments conducted, we observed that node location affects communication. We found out that the human body acts as a barrier against communication, that takes places between nodes positioned on each side. Hence, the human body caused some nodes to have higher or lower PRR values as compared to other nodes.

- We noticed that the human body itself, not only affected radio propagation but also led to attenuations in signal levels received by on-body sensors, as a result of which the nodes had varied connectivity between them. Our results also showed that PRR and RSSI values may be affected by the environment of the experiment. PRR and RSSI had direct correlations to transmission power.

- Comparing certain results to [13], we observed that the mica2dot radios which have a frequency of 433 MHz permeate the human body better as compared to MicaZ radios having a frequency of 2.4 GHz.

5.2 Future Work

The results obtained can be used to design sustainable reliable on-body sensor networks, while maximizing the networks lifetime and minimizing RF power required per node.

We can explore different power levels to select an optimum power level that maximizes energy efficiency and reduces human exposure to electromagnetic radiation.

We can use various body postures and see how daily human activities affect these values, based on the different environments. In addition, it would be interesting to see how the results would vary on adding more nodes on the human body.

Protocols could be designed to avoid the dropping of packets by detecting collisions for the case of multiple senders scenario.

Appendix

The results obtained by performing all the above mentioned experiments are presented in the tables below.

Table 5.1 and Table 5.2 presents the PRR and RSSI values for Experiment 1.

Table 5.3 and Table 5.4 presents the PRR and RSSI values for Experiment 2.

Table 5.5 - Table 5.10 presents the PRR values, and Table 5.11 - Table 5.16 presents the RSSI values for Experiment 3 at -25dBm, -15 dBm and -10 dBm transmission power levels.

Table 5.17 - Table 5.22 presents the PRR values, and Table 5.23 - Table 5.28 presents the RSSI values for Experiment 4 and Experiment 5 at -25dBm, -15 dBm and -10 dBm transmission power levels.

Table 5.1: Experiment 1: PRR vs Transmission Power

Distance (ft.)	**PRR -25dBm**	**PRR -15dBm**	**PRR -10dBm**
1	98	99	100
2	98	99	100
3	98	99	100
4	98	99	100
5	98	99	100
10	97	98	99

Table 5.2: Experiment 1: RSSI vs Transmission Power

Distance (ft.)	**RSSI -25dBm**	**RSSI -15dBm**	**RSSI -10dBm**
1	-66	-64	-62
2	-66	-64	-62
3	-66	-64	-62
4	-66	-64	-62
5	-66	-64	-62
10	-67	-65	-63

Table 5.3: Experiment 2: PRR vs Transmission Power

Distance (ft.)	**PRR -25dBm**	**PRR -15dBm**	**PRR -10dBm**
1	92	95	97
2	90	94	96
3	88	93	95
4	87	92	94
5	85	91	93
10	82	90	92

Table 5.4: Experiment 2: RSSI vs Transmission Power

Distance (ft.)	**RSSI -25dBm**	**RSSI -15dBm**	**RSSI -10dBm**
1	-70	-60	-50
2	-72	-62	-52
3	-74	-64	-54
4	-78	-70	-60
5	-82	-78	-64
10	-92	-89	-83

Table 5.5: Node 1: PRR vs Number of Senders

1	**2**	**3**	**5**
98	95	91	86
98	94	90	
98	95	90	
98	94	91	
98	94	91	
	95	90	
	95	90	
	95	90	
	94	92	
	94	91	
99	97	95	87
99	96	94	
99	97	94	
99	97	94	
99	97	95	
	97	94	
	97	94	
	96	94	
	96	95	
	96	94	
100	99	97	89
100	98	96	
100	98	96	
100	98	96	
100	98	97	
	99	96	
	99	96	
	99	96	
	98	97	
	98	96	

Table 5.6: Node 2: PRR vs Number of Senders

1	**2**	**3**	**5**
98	95	90	85
98	94	91	
98	95	92	
98	95	90	
98	94	92	
	95	90	
	95	91	
	94	91	
	95	90	
	94	92	
99	97	94	88
99	96	95	
99	97	95	
99	97	95	
99	96	95	
	97	94	
	97	95	
	96	95	
	96	94	
	96	95	
100	98	96	89
100	98	96	
100	99	97	
100	98	97	
100	98	97	
	98	96	
	99	96	
	98	96	
	99	96	
	98	97	

Table 5.7: Node 3: PRR vs Number of Senders

1	**2**	**3**	**5**
98	94	91	86
98	95	91	
98	95	90	
98	95	92	
98	95	92	
	96	90	
	94	90	
	95	92	
	95	90	
	94	90	
99	97	95	87
99	96	95	
99	97	94	
99	96	94	
99	96	95	
	97	94	
	96	94	
	97	95	
	96	94	
	96	94	
100	98	97	88
100	98	97	
100	98	96	
100	98	96	
100	99	97	
	98	96	
	99	96	
	99	97	
	98	96	
	98	96	

Table 5.8: Node 4: PRR vs Number of Senders

1	**2**	**3**	**5**
98	95	90	86
98	95	90	
98	95	92	
98	95	92	
98	95	90	
	94	92	
	95	91	
	95	90	
	95	91	
	95	91	
99	97	94	87
99	97	94	
99	97	95	
99	97	95	
99	97	95	
	96	95	
	97	95	
	96	94	
	96	95	
	97	95	
100	98	96	88
100	99	96	
100	99	97	
100	98	96	
100	98	97	
	98	97	
	99	97	
	98	96	
	98	97	
	99	97	

Table 5.9: Node 5: PRR vs Number of Senders

1	**2**	**3**	**5**
98	94	91	85
98	95	90	
98	94	90	
98	95	91	
98	95	91	
	95	90	
	94	90	
	94	91	
	95	90	
	95	91	
99	97	95	88
99	97	94	
99	96	94	
99	96	95	
99	96	95	
	97	94	
	96	94	
	96	94	
	96	94	
	97	94	
100	98	97	89
100	99	96	
100	98	96	
100	98	97	
100	98	97	
	98	96	
	98	96	
	98	96	
	98	96	
	99	96	

Table 5.10: Node 6: PRR vs Number of Senders

1	**2**	**3**	**5**
98	94	90	86
98	95	92	
98	95	90	
98	94	90	
98	95	90	
	95	90	
	94	92	
	95	90	
	94	91	
	95	91	
99	96	94	88
99	97	95	
99	97	94	
99	96	94	
99	97	95	
	97	94	
	96	95	
	96	94	
	96	95	
	97	95	
100	98	96	89
100	98	97	
100	99	96	
100	98	96	
100	98	97	
	98	96	
	98	97	
	98	96	
	98	97	
	99	97	

Table 5.11: Node 1: RSSI vs Number of Senders

1	**2**	**3**	**5**
-68	-65	-63	-61
-66	-64	-62	
-68	-64	-62	
-67	-64	-62	
-68	-64	-63	
	-65	-62	
	-65	-62	
	-64	-62	
	-64	-63	
	-65	-62	
-65	-61	-59	-57
-63	-62	-60	
-65	-63	-60	
-64	-63	-60	
-65	-63	-59	
	-61	-60	
	-61	-60	
	-62	-60	
	-62	-59	
	-61	-60	
-61	-57	-55	-54
-60	-57	-56	
-62	-58	-56	
-61	-58	-56	
-62	-58	-55	
	-57	-56	
	-57	-56	
	-57	-56	
	-57	-55	
	-57	-56	

Table 5.12: Node 2: RSSI vs Number of Senders

1	**2**	**3**	**5**
-68	-65	-62	-60
-68	-64	-63	
-66	-65	-63	
-68	-65	-62	
-67	-64	-62	
	-64	-62	
	-64	-62	
	-64	-62	
	-65	-62	
	-64	-63	
-65	-61	-60	-58
-65	-62	-59	
-63	-61	-59	
-65	-61	-60	
-64	-62	-60	
	-63	-60	
	-63	-60	
	-63	-60	
	-61	-60	
	-62	-59	
-61	-57	-56	-54
-62	-57	-55	
-60	-57	-55	
-62	-57	-56	
-61	-57	-56	
	-58	-56	
	-58	-56	
	-58	-56	
	-57	-56	
	-57	-55	

Table 5.13: Node 3: RSSI vs Number of Senders

1	**2**	**3**	**5**
-66	-64	-62	-60
-68	-64	-63	
-67	-64	-62	
-66	-64	-62	
-68	-64	-63	
	-65	-62	
	-64	-62	
	-64	-63	
	-64	-62	
	-64	-62	
-63	-62	-60	-58
-65	-62	-59	
-64	-63	-60	
-63	-63	-60	
-65	-63	-59	
	-61	-60	
	-62	-60	
	-62	-59	
	-62	-60	
	-62	-60	
-60	-57	-56	-54
-62	-57	-55	
-61	-58	-56	
-60	-58	-56	
-62	-58	-55	
	-57	-56	
	-57	-56	
	-57	-55	
	-57	-56	
	-57	-56	

Table 5.14: Node 4: RSSI vs Number of Senders

1	**2**	**3**	**5**
-68	-64	-62	-61
-66	-64	-62	
-67	-64	-63	
-68	-64	-62	
-66	-65	-62	
	-64	-62	
	-64	-63	
	-64	-62	
	-64	-62	
	-64	-63	
-65	-62	-60	-57
-63	-62	-60	
-64	-62	-59	
-65	-62	-60	
-63	-61	-60	
	-63	-60	
	-62	-59	
	-63	-60	
	-63	-60	
	-62	-59	
-62	-57	-56	-54
-60	-57	-56	
-61	-57	-55	
-62	-57	-56	
-60	-57	-56	
	-58	-56	
	-57	-55	
	-58	-56	
	-58	-56	
	-57	-55	

Table 5.15: Node 5: RSSI vs Number of Senders

1	**2**	**3**	**5**
-67	-64	-62	-60
-68	-64	-63	
-66	-64	-62	
-68	-64	-63	
-67	-64	-63	
	-65	-62	
	-64	-62	
	-64	-62	
	-64	-62	
	-64	-62	
-64	-62	-60	-58
-65	-62	-59	
-63	-63	-60	
-65	-63	-59	
-64	-63	-59	
	-61	-60	
	-62	-60	
	-62	-60	
	-62	-60	
	-62	-60	
-61	-57	-56	-54
-62	-57	-55	
-60	-58	-56	
-62	-58	-55	
-61	-58	-55	
	-57	-56	
	-57	-56	
	-57	-56	
	-57	-56	
	-57	-56	

Table 5.16: Node 6: RSSI vs Number of Senders

1	**2**	**3**	**5**
-68	-64	-63	-61
-67	-64	-62	
-68	-65	-62	
-66	-64	-62	
-67	-64	-62	
	-64	-62	
	-64	-63	
	-64	-63	
	-64	-62	
	-64	-62	
-65	-62	-59	-58
-64	-62	-60	
-65	-61	-60	
-63	-62	-60	
-64	-62	-60	
	-63	-60	
	-62	-59	
	-62	-59	
	-63	-60	
	-63	-60	
-62	-57	-55	-54
-61	-57	-56	
-62	-57	-56	
-60	-57	-56	
-61	-57	-56	
	-58	-56	
	-57	-55	
	-57	-55	
	-58	-56	
	-58	-56	

Table 5.17: Left Ankle: PRR vs Number of Senders

1	**2**	**3**	**5**
95	86	77	66
96	82	75	
93	85	75	
92	84	76	
95	84	76	
	86	77	
	85	75	
	86	75	
	83	77	
	83	76	
98	88	80	68
98	86	77	
96	87	78	
96	87	78	
98	87	79	
	88	78	
	87	78	
	86	78	
	85	80	
	85	78	
99	89	80	68
99	87	82	
98	88	81	
97	87	81	
99	87	82	
	89	81	
	89	81	
	89	81	
	87	83	
	87	81	

Table 5.18: Right Ankle: PRR vs Number of Senders

1	**2**	**3**	**5**
95	85	75	65
95	83	77	
95	86	77	
93	85	75	
94	84	77	
	85	75	
	86	76	
	82	76	
	86	75	
	82	77	
98	87	77	67
97	85	79	
98	88	80	
95	87	80	
96	86	80	
	87	78	
	87	79	
	86	79	
	86	78	
	86	80	
99	88	80	69
98	88	82	
99	89	83	
98	89	83	
98	87	83	
	88	81	
	89	82	
	87	82	
	89	81	
	87	83	

Table 5.19: Left Waist: PRR vs Number of Senders

1	**2**	**3**	**5**
95	84	79	61
96	85	76	
95	85	75	
95	85	77	
96	85	77	
	86	75	
	84	75	
	85	77	
	85	75	
	84	75	
98	88	82	64
97	86	77	
97	87	78	
96	86	78	
98	86	80	
	88	78	
	85	78	
	87	80	
	85	78	
	86	78	
99	88	85	67
98	88	78	
99	88	79	
98	88	80	
99	89	83	
	87	81	
	89	81	
	89	83	
	87	81	
	88	81	

Table 5.20: Right Waist: PRR vs Number of Senders

1	**2**	**3**	**5**
96	85	79	61
93	86	76	
96	86	75	
96	85	77	
94	85	75	
	84	77	
	86	76	
	85	75	
	85	76	
	86	76	
97	87	82	63
96	87	77	
98	88	77	
97	87	79	
97	87	80	
	86	80	
	87	79	
	85	78	
	85	79	
	87	79	
98	88	85	66
96	89	78	
99	89	79	
99	88	80	
98	88	83	
	87	83	
	89	82	
	87	81	
	87	82	
	89	82	

Table 5.21: Left Arm: PRR vs Number of Senders

1	**2**	**3**	**5**
93	83	77	65
94	86	76	
96	84	78	
95	85	76	
94	85	76	
	86	75	
	83	75	
	82	76	
	86	75	
	86	76	
97	87	80	67
98	88	79	
98	86	79	
97	86	79	
97	86	79	
	88	78	
	86	78	
	85	78	
	86	78	
	87	78	
98	88	82	68
99	89	81	
99	87	80	
98	88	82	
98	88	82	
	89	81	
	87	81	
	87	81	
	88	81	
	89	81	

Table 5.22: Right Arm: PRR vs Number of Senders

1	**2**	**3**	**5**
94	84	76	66
92	85	77	
95	86	76	
96	84	75	
95	85	75	
	85	75	
	82	77	
	86	75	
	83	76	
	86	76	
96	86	79	68
95	87	80	
97	88	78	
98	86	78	
98	87	80	
	87	78	
	85	80	
	86	78	
	86	79	
	87	79	
97	87	81	69
96	88	82	
98	89	79	
99	87	81	
99	88	83	
	88	81	
	87	83	
	88	81	
	87	82	
	89	82	

Table 5.23: Left Ankle: RSSI vs Number of Senders

1	**2**	**3**	**5**
-75	-71	-68	-64
-74	-72	-69	
-77	-73	-70	
-76	-73	-69	
-77	-73	-68	
	-71	-69	
	-71	-69	
	-72	-69	
	-72	-68	
	-71	-68	
-70	-65	-62	-61
-68	-66	-63	
-71	-67	-64	
-69	-67	-63	
-71	-67	-62	
	-65	-63	
	-65	-63	
	-66	-63	
	-66	-62	
	-65	-63	
-65	-61	-57	-56
-64	-61	-58	
-66	-62	-59	
-65	-62	-58	
-66	-62	-57	
	-60	-58	
	-61	-58	
	-61	-58	
	-61	-57	
	-61	-58	

Table 5.24: Right Ankle: RSSI vs Number of Senders

1	**2**	**3**	**5**
-75	-71	-69	-63
-77	-72	-68	
-74	-71	-68	
-77	-71	-69	
-76	-72	-70	
	-73	-69	
	-73	-69	
	-73	-69	
	-71	-69	
	-72	-68	
-70	-65	-63	-61
-71	-66	-62	
-68	-65	-62	
-71	-65	-62	
-69	-66	-63	
	-67	-63	
	-67	-63	
	-67	-63	
	-65	-63	
	-66	-62	
-65	-61	-58	-56
-66	-61	-57	
-64	-61	-57	
-66	-60	-58	
-65	-61	-59	
	-62	-58	
	-62	-58	
	-62	-58	
	-61	-58	
	-61	-57	

Table 5.25: Left Waist: RSSI vs Number of Senders

1	**2**	**3**	**5**
-74	-72	-69	-62
-75	-72	-68	
-76	-73	-69	
-74	-73	-69	
-76	-73	-68	
	-71	-68	
	-72	-70	
	-72	-68	
	-72	-69	
	-72	-69	
-68	-66	-63	-60
-70	-66	-62	
-69	-67	-63	
-68	-67	-63	
-70	-67	-62	
	-65	-63	
	-66	-64	
	-66	-62	
	-66	-63	
	-66	-63	
-64	-61	-58	-56
-66	-61	-57	
-65	-62	-58	
-64	-62	-58	
-66	-62	-57	
	-60	-58	
	-61	-59	
	-61	-57	
	-61	-58	
	-61	-58	

Table 5.26: Right Waist: RSSI vs Number of Senders

1	**2**	**3**	**5**
-76	-72	-69	-61
-74	-72	-68	
-75	-72	-68	
-76	-72	-69	
-74	-71	-70	
	-73	-69	
	-72	-68	
	-73	-69	
	-73	-69	
	-72	-68	
-70	-66	-63	-59
-68	-66	-63	
-69	-66	-62	
-70	-66	-63	
-68	-65	-64	
	-67	-63	
	-66	-62	
	-67	-63	
	-67	-63	
	-66	-62	
-66	-61	-58	-56
-64	-61	-58	
-65	-61	-57	
-66	-61	-58	
-64	-60	-59	
	-62	-58	
	-61	-57	
	-62	-58	
	-62	-58	
	-61	-57	

Table 5.27: Left Arm: RSSI vs Number of Senders

1	**2**	**3**	**5**
-76	-72	-69	-63
-76	-72	-68	
-75	-73	-69	
-74	-73	-68	
-75	-73	-68	
	-71	-69	
	-72	-70	
	-72	-69	
	-72	-69	
	-72	-69	
-69	-66	-63	-61
-70	-66	-62	
-68	-67	-63	
-70	-67	-62	
-69	-67	-62	
	-65	-63	
	-66	-64	
	-66	-63	
	-66	-63	
	-66	-63	
-65	-61	-58	-56
-66	-61	-57	
-64	-62	-58	
-66	-62	-57	
-65	-62	-57	
	-60	-58	
	-61	-59	
	-61	-58	
	-61	-58	
	-61	-58	

Table 5.28: Right Arm: RSSI vs Number of Senders

1	**2**	**3**	**5**
-76	-72	-68	-64
-76	-72	-69	
-74	-71	-69	
-75	-72	-69	
-75	-72	-70	
	-73	-69	
	-72	-68	
	-72	-68	
	-73	-69	
	-73	-69	
-70	-66	-62	-62
-69	-66	-63	
-70	-65	-63	
-68	-66	-62	
-69	-66	-64	
	-67	-63	
	-66	-62	
	-66	-62	
	-67	-63	
	-67	-63	
-66	-61	-57	-56
-65	-61	-58	
-66	-60	-58	
-64	-61	-58	
-65	-61	-59	
	-62	-58	
	-61	-57	
	-61	-57	
	-62	-58	
	-62	-58	

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