Wearable Honeypot

A Major Qualifying Project Report:

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Abstract

Wearable embedded devices are in common use in the medical industry. In today’s society security is needed in just about every electronic device. However, these devices don't yet have many security standards. To prevent scenarios that involve unauthorized sources intruding on a device, a honeypot could be used as a secure lightweight (in terms of resource usage) addition to these medical devices. This project seeks to devise and implement a wearable honeypot to add security to a BAN (Body Area Network).

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1 Introduction

In this modern information age, *wearable embedded devices* (small sensors with microcontrollers equipped with wireless communication) have become common use in the medical industry [10]. More recently a consumer market has developed for these kinds of devices [9]. Wearable embedded devices connected to a basestation form a *piconet* (small network) called a *BAN* (Body Area Network AKA Body Sensor Network). Currently, most implementations of BANs are used by the medical industry because by attaching multiple sensors to someone, different medical stats can be gathered and then analyzed by a doctor in the treatment of a patient [1]. With the advent of products such as the Apple Watch, BANs are moving into broader consumer use. With small sensors, the user can usually maintain a normal lifestyle even with all the monitoring. A BAN is shown below in Figure 1.

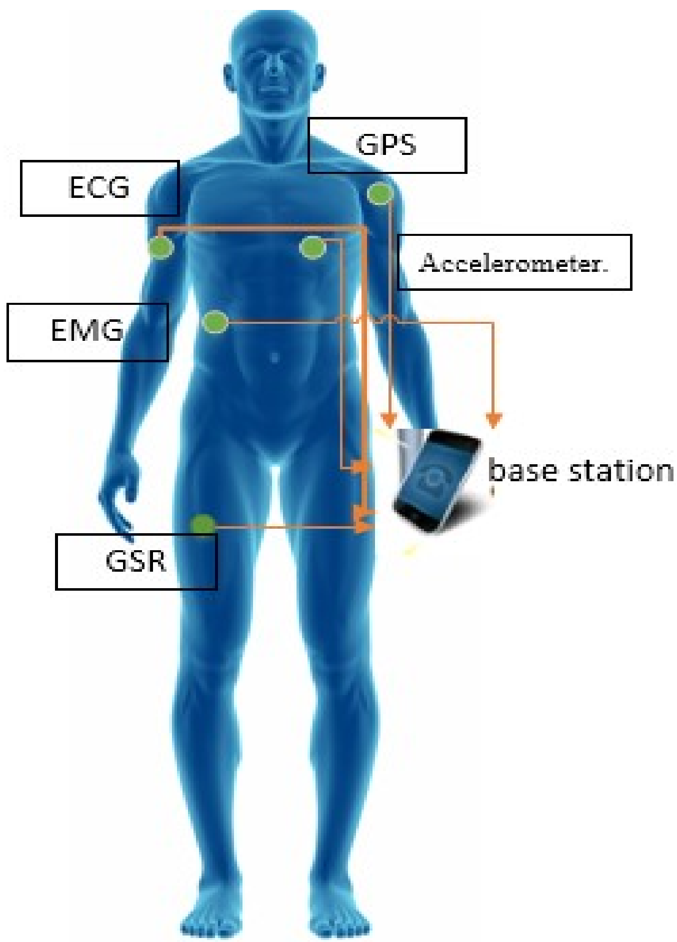


Figure 1: Wireless BAN

The work to be presented here is built on a Bluetooth-based BAN system built on the *Shimmer platform*, and utilizes a BAN-PnP application-layer protocol [19]. The BAN has a *basestation* implemented as an Android app; the *motes* (node on sensor network) in the sensor network are Shimmer motes running TinyOS [1]. The BAN itself already provides a measurable hit to the performance of the motes [1]. This highlights the need for lightweight security protocols. This BAN is ideal for the purposes of this project as it is cross platform. It only requires a device to implement the BAN protocol on top of Bluetooth. Importantly this BAN is plug and play and basestation firmware does not need to be updated to accommodate new motes with previously unknown functionality [1]. Generally, these wireless devices are short ranged, however this does not shield users from attackers. Some of these medical devices in BANs could be harmful to the user if tampered with.

Today security is needed in just about every electronic device, however BAN devices don't yet have many security standards. Standard security options are ill-suited to BANs because motes run on batteries and standard security solutions don’t take this into account. Standard security solutions include public key cryptography and block ciphers, which are great for desktop applications that need encryption. However these require a lot of computation to encrypt and decrypt messages. To prevent unauthorized sources from intruding on a device, a *honeypot* could be used as a lightweight addition to these medical devices.

Honeypots are traps that are meant for attacker to attack. They are meant to be attacked so that someone can detect the presence of attackers or to gain more information about what kinds of attacks can be launched. Honeypots typically have a monitoring component. This allows a system designer to log and recreate exploits so that they can be patched [15]. Most of the time, when no threats are present, the honeypot requires little computation and therefore doesn’t use much battery power. Additionally, when a threat is detected heavier weight security measures (i.e. thorough packet sniffing and analysis) can be activated [14]. These heavier weight security measures would produce a significant drain on battery power if they were always active. Previous honeypots are mostly used in enterprise environments. These are typically set up connected to web servers, but are not supposed to be used for legitimate purposes, so only attackers interact with them.

Recently, there have been groups working on *mobile honeypots*, which are essentially mobile versions (as in smart phones) of *enterprise honeypots*. A notable mobile honeypot, *HoneyDroid* extensively monitors all communications in and out of the smart phone [5]. This was extended in *HoneyDroid Extension* to rooted smart phones [4]. These are not good in this case because they only apply to phones and the thorough communication analysis is battery intensive. Other mobile honeypots throw together existing honeypots [7] (so they don't apply to BANs) or open up new avenues of attack by communicating with the Internet [6]. This honeypot is a new application, however many design principles will remain the same as traditional honeypots.

This project sought to devise and implement a *Wearable Honeypot* to add security to a BAN. This honeypot system utilizes the basestation and some dedicated helper motes. They can communicate in the open or pass secret messages through an encrypted channel. The motes attract an attacker to interact with them by being the most active members of the BAN. The basestation knows what every single message the helper motes send it will be. To do this the honeypot deterministically synthesizes and streams accelerometer data. The basestation then verifies that the messages come as expected using a robust mechanism that allows for packet loss due to noisy networks. The helper motes also know what kinds of messages to expect from the basestation and when it should receive certain messages and not others. Since the basestation knows everything the helper motes will send and the helper motes know what kinds of messages they're supposed to receive, the honeypot is able to know when an attacker starts to interact with it. This honeypot is one of if not the first honeypot solution for a BAN and computationally less expensive than using standard security solutions. This solution is able to secure a BAN for a longer period without impacting the battery life of the actual vital sensors the user has in their BAN.

The discussion will start with background information about Bluetooth and Honeypots in section 2. In section 3 is the problem statement. This is followed by the motivations for coming up with a solution in section 4. Next is a discussion of the related works of mobile honeypots in section 5. Section 6 is the system model where the BAN the *Wearable Honeypot* is built on and the threat model are discussed. After that, the design of this honeypot is documented in section 7. The testing and results will be presented in section 8. Section 9 contains the conclusions of this project. Finally in section 10 improvements to the system and next steps are suggested.

2 Background

To understand this project, a basic understanding of Bluetooth and honeypots is required. Bluetooth is used as the means of communication within a BAN and operates at similar frequencies to Wi-Fi [27]. This project aims to design a honeypot to detect attacks on a BAN, which can be used to improve the security of the BAN.

2.1 Bluetooth

Bluetooth is a peer to peer communication protocol over a short range broadcast medium. In a Bluetooth piconet there is one master and up to 7 slaves. The master initiates activities and slaves respond to the master. To add a slave to the piconet a master must initiate pairing with a slave. When communicating, the master hops between 7 channels and the slaves hop between another 7 channels to send packets. Bluetooth operates in the 2.4-2.485 GHz data range [26]. Like TCP/IP, it has a stack to abstract out the hardware from the application programmer. Bluetooth is also widely used, despite known vulnerabilities and demonstrated hacks [22].

2.2 Honeypots

A honeypot is best understood as a trap for attackers [14]. A honeypot is a system whose main purpose is to be attacked and compromised [5]. They monitor what goes in and what goes out of a system and are isolated, sometimes even running on a separate device. Some honeypots act as a decoy server that tries to compromise the attack and make themselves easy targets [16]. Honeypots can log all the incoming and outgoing packets so any vulnerability can be looked back on and analyzed for future study. There are scenarios where multiple different honeypots are used within a system. This is referred to as a honeynet [13].

There are many advantages to a honeypot. One advantage is that a honeypot can record illegitimate activity. They are usually encrypted environments, and don't require known attack signatures [15]. But like all things, the honeypot has some disadvantages too. For instance, there are some types of honeypots that can be used to attack other systems. Also, a honeypot cannot detect if other systems are being attacked. It only knows what is going in and out of its own system. A honeypot may also be detected by the attacker.

2.2.1 Honeypot Classification

While there are different applications and implementations of honeypots, they fall into a couple archetypes based upon purpose and implementation. Usually they're either *passive or* *active*. Passive honeypots collect data for analysis so exploits can become known and patched. Active honeypots detect threats and then do something in response. Honeypots are usually *high interaction or low interaction*. Low interaction honeypots recreate small subsets of a system, are generally simple, and not resource intensive. High interaction honeypots recreate entire subsystems resulting in higher security at the expense of maintenance costs. The extreme case of a high interaction honeypot would be a pure honeypot. In a pure honeypot the entire system is a honeypot, not a mix of simulated subsystems. In terms of purpose, there are two main types of classification, enterprise and research honeypots. *Research honeypots* are typically passive honeypots that collect extensive information about hacks and exploits and are generally used for research, hence the name. The other kind is an *enterprise honeypot*. Typically enterprise honeypots are low interaction, or made with multiple low interaction implementations. This is for practicality purposes because they are easier to deploy and maintain. After all they are made for production environments.

3 Problem Statement

Standard security solutions involve cryptography, which can be computationally intensive. Given that the security solution must be cross platform, security options are further reduced to standard block ciphers or standard public key ciphers. Most available for TinyOS is the AES block cipher. This would have to be used in an operating mode such as *cipher block chaining* to be effective, not just straight encryption. This adds even more to the computational overhead.

The challenge of this project is to develop an effective honeypot that doesn't greatly diminish the performance of the devices in a BAN. Meanwhile it still must monitor effectively enough to detect attacks on the BAN. Just running the BAN protocol has already affected mote battery life [1]. The high level design goals of the Honeypot were as follows:

- Obvious enough to be an attack target, but not obviously a honeypot.
- Effectively detects attacks
- Shouldn’t be a large burden on the power requirements of the embedded sensors.
- To be specific to a Bluetooth BAN

4 Motivations

Mobile honeypots are a new field and BAN honeypots don't yet exist. Wearable embedded devices do not have much security [17]. They can include modern pacemakers or glucose meters. Thus one of the chief motivations of this project is to make these devices safe to use [14]. Wearable embedded devices also have strict battery requirements meaning that any security measures would have to be lightweight. In a passive state a honeypot doesn't necessarily require a lot of computational overhead. To make these devices safe in a practical way, the flexibility of a honeypot is desirable; standard cryptographic routines are not desirable because they are computationally expensive. Finally, there is a need to secure vital wearable embedded devices to be safe to use and this will take more than just implementing standard security.

5 Related Works

Examples of enterprise Honeypots are Google Honeypot, Honeyd, Homemade honeypot, ManTrap and BackOfficer Friendly [13]. In the new field of mobile honeypots there are HoneyDroid, HoneyDroid Extension, Mobile Honeynet, and Mobile Communication Honeypot to name a few. The following info graphic in Figure 7 visualizes a taxonomy and classification of well-known honeypots and the mobile honeypots discussed in Figure 2. Some of the mobile honeypots are in the early stages of design and therefore couldn't thoroughly be classified.

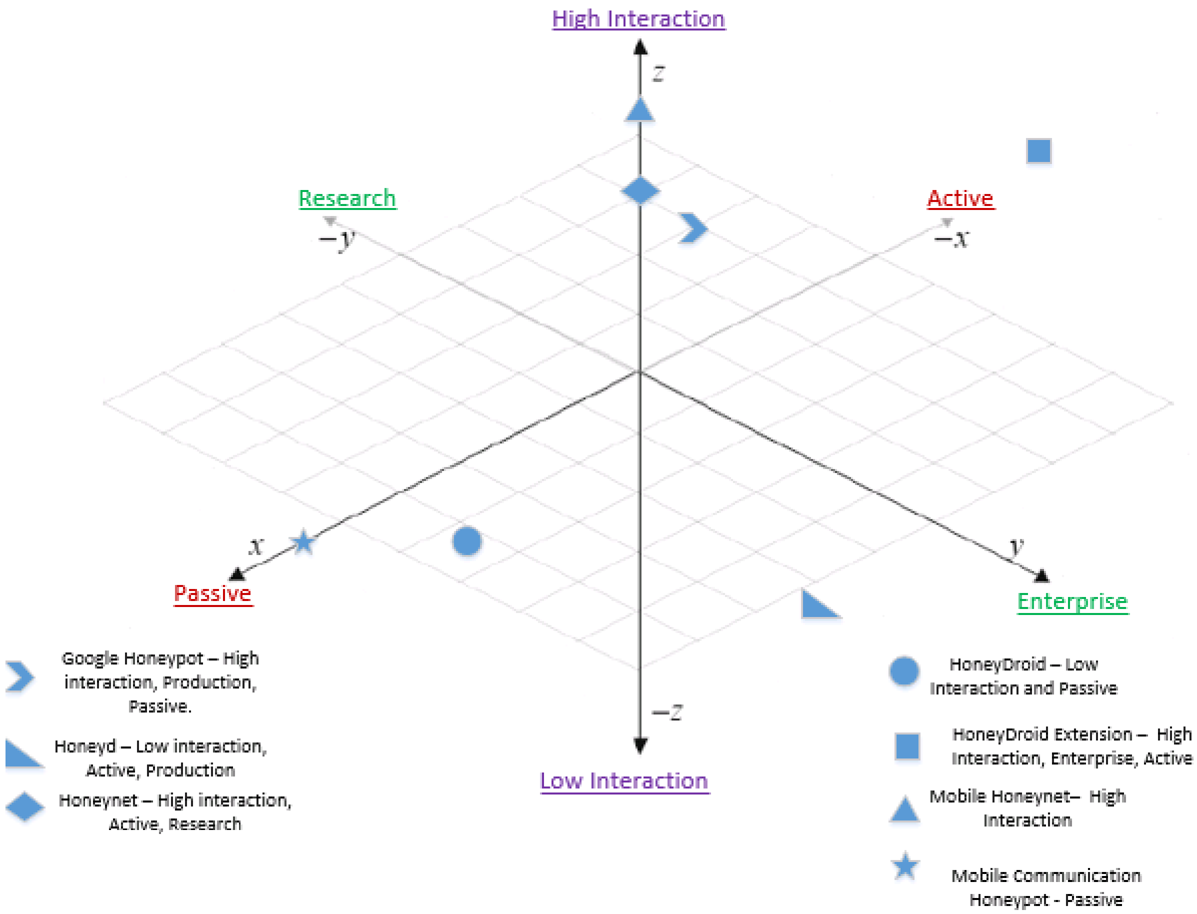


Figure 2: Classification of Honeypots

For out purposes, enterprise honeypots aren't very relevant, so the following examination of honeypots will focus on existing mobile honeypots.

5.1 HoneyDroid

One example of a mobile honeypot is the *HoneyDroid* [5]. This honeypot system deals with 4 challenges: *monitoring, audit logging, containment* and *visibility.* The monitoring issue involved how to monitor everything occurring in the system without causing the OS to be easily compromised [5]. The goal in monitoring is to have a system that can monitor everything such that they can recreate the exact event. The audit logging issue is about creating a secure, reliable storage compartment of all the logs. In containment, the honeypot has to be designed such that the attacker is able to easily stumble into it but becomes trapped in the honeypot and isn't able to make any further attacks [5]. The issue with visibility is that the honeypot needs to be exposed enough so that the attacker can attack it, but not so visible that it's obvious and easy to get around [5]. The design of the *HoneyDroid* is shown below in Figure 3:

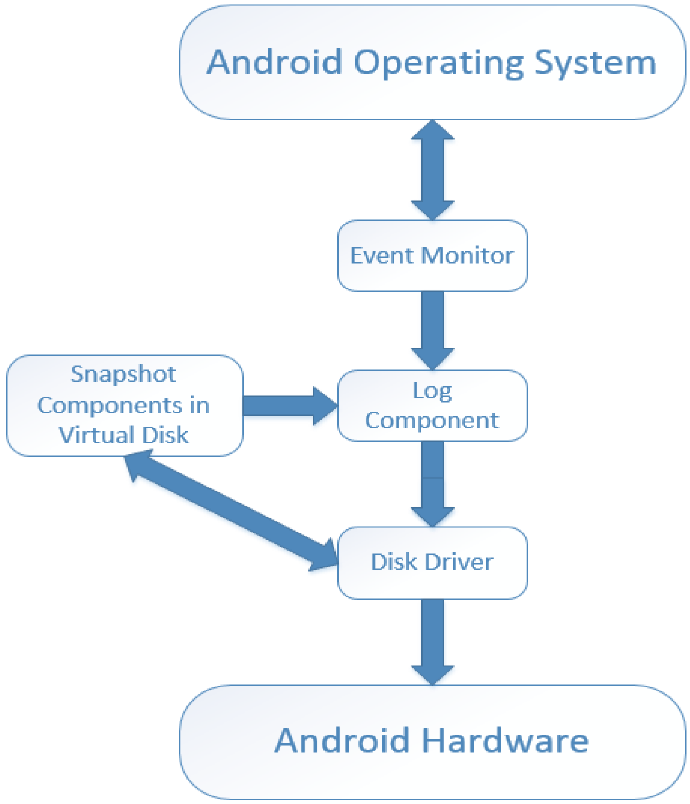


Figure 3: Design of HoneyDroid

In this diagram the *Event Monitor* is placed in between the Android OS and Android's own form of Event Monitor that monitors calls and signals. In *HoneyDroid* the Android OS is not able to have direct access to the hardware. Instead, *HoneyDroid* virtualizes everything thus allowing everything to be monitored. This also allows them to take snapshots of the system. In this system, the Android OS has no access to the snapshots either; the virtual modem is used to fight against malware, leading to the containment functionality [5].

The *log component* receives information from different areas of the system. These logs ensure integrity through time stamps. [5]. For *visibility*, this honeypot is given a public IP address. It is planned for *HoneyDroid* to have automatic installation and execution privileges, and give the honeypot access to the internet and allow the honeypot to spread the google account name associated with the honeypot. [5].

HoneyDroid seems to be a great system to reference the wearable honeypot. Monitoring, audit logging, containment and visibility are key components needed for the wearable honeypot specific system. Specifications of where certain components are stationed may alter however the idea of time stamping all components that enter and leave the honeypot, the ability to snapshot system activities and the honeypot given a public IP all seems promising for the wearable honeypot system. However, while this honeypot contains many useful properties, it simply doesn't provide security to Bluetooth and only applies to the mobile phone, not to a BAN. Also, the thorough packet sniffing and analysis of everything coming in and out of the system is computationally intensive.

5.2 HoneyDroid Extension

Extending from the *HoneyDroid*, lack of behavioral considerations and existing security policy on the mobile device platform became additional challenges. The lack of behavioral considerations means mobile users desire to give up security in return for free access to applications. This means it’s hard to take into account user actions such as rooting their phones or installing malicious applications. The second challenge involved how certain Android functions limited the honeypot functionality. These Android functions include things that are able to bypass the Android security such as SMS and MMS [4]. Figure 4 bellow illustrates the framework for this mobile honeypot.

Figure 4: HoneyDroid Extension

In this scenario, this mobile honeypot is intended for threats coming from data networks that are connected telecommunication cells [4]. The connection for the smart mobile honeypots comes through from telecommunication stations, Wi-Fi and Bluetooth. The smart mobile honeypots have 2 states: state 1 *records data* and connects to web server to send this data; state 2 involves *threat monitoring, audit logging, containment* and *modeling functionalities*.

State 1 has a honeypot that communicates with other honeypots. Specifically when data is being sent from the device, it goes through a honeypot which communicates with other servers with honeypots. Then when data is being sent back the honeypot records everything coming in [4]. State 2 is a software implementation of threat monitoring, audit logging, containment and user’s behavioral logging requirements. Thread monitoring is responsible for monitoring data packets going in and out of the system. When a threat is detected, it will gather data focused around that attack. The audit logging will be a copy of the gathered data and will be backed up on another server. For containment, the honeypot will isolate the attack and not let it continue on through the network. If there was an occurrence of a fast speeding threat, the mobile device will be cut off from the network. Another module called *User Behavioral Module* will be monitoring and tracking the user's patterns [4].

The additions to the *HoneyDroid* seem plausible. However, for the BAN honeypot it is assumed the user is not interested in lowering its security and rooting their Android device. Communicating with other honeypot devices for stronger security is also not in the scope of this project. Like with the original *HoneyDroid* the thorough packet analysis is computationally intensive. This idea may be used for future works but is not useful for the design of the BAN honeypot.

5.3 Mobile Honeynet

The implementation of *Mobile Honeynet* was based on 3 main questions:

1) Is it necessary that the probe runs on a mobile device
2) Is it necessary that the honeypot runs on a mobile OS
3) To which network is the mobile honeypot connected

This system made the assumption that there is no need to have a mobile honeypot on a smartphone [7]. Instead a Linux operating system was used for 2 reasons. One, most smartphones use Android OS and, two, it allows you to reuse existing honeypot tools [7]. To answer the third question, the mobile probe should connect to a real mobile network. If not, there is a chance the attacker can detect differences.

The implementation of this mobile honeypot consisted of three other honeypots: *Kippo, Glastopf* and *Dionaea*. *Kippo* is an SSH honeypot that has a trivial password. This allows the attacker to gain access into the system. The attacker is given administrator privileges where the attacker can execute common programs, download and install anything else they wanted. In the background the honeypot records everything and uses it later for analysis. To prevent more problems for the honeypot, executing newly installed programmers are prohibited.

The second honeypot, *Glastopf* provides uploads to web-based servers. This honeypot monitors and watches this upload and logs everything that comes in and out of this uploaded file. And finally, *Dionaea* is a honeypot that monitors all transport ports.

For the BAN honeypot, this honeynet system cannot be referenced. This honeynet system regards the fact a mobile honeypot is needed and attempts to utilize other manufactured honeypots. The manufactured honeypots don't apply to the BAN.

5.4 Mobile Communication Honeypot

The final system had an interesting way of implementing their mobile honeypot. The design is shown below in Figure 5 [6].

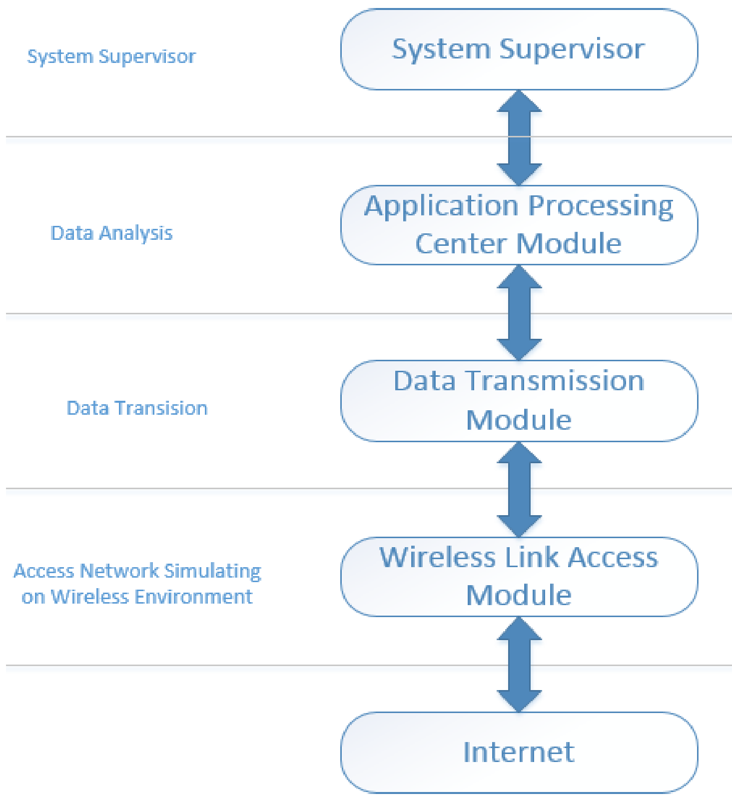


Figure 5: Mobile Communication Honeypot

As this figure shows the honeypot is broken down into four layers: *access, networking simulating wireless environment, data transmission, data analysis* and *system supervisor*. Within these layers mobile communication terminals, wireless link access module, data transmission module and application processing center module [6].

This communication honeypot cannot be referenced when designing the BAN honeypot. Even though this system is plausible, the BAN communicates through Bluetooth and does not require the Internet. Additionally communicating through the internet is another security vulnerability to be aware of.

6 System Model

6.1 BAN

The system the honeypot is built on is a plug and play BAN protocol. The BAN consists of a basestation (BS) and sensor nodes or motes. The topology of the BAN is shown below in figure 6:

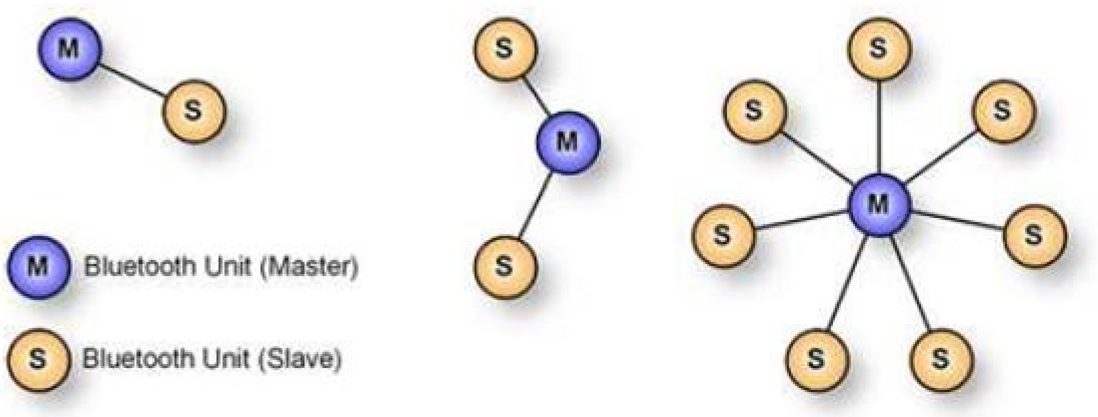


Figure 6: BAN Topology

The BAN was designed as a link layer protocol with these properties:

- Does not inherently rely on static message identifiers,
- Supports new sensors, motes, and commands without changes to the mote firmware or basestation application
- Have a flexible basestation learning language that can be expanded easily through changes to a few Grammars and
- Have a BAN platform that is flexible enough to support any type of research or real world application.[1]

In creating this BAN protocol, a platform was needed. For a mobile device, the team decided on the Android platform due to its wide usage across many different devices. For a sensing platform, they decided on the *Shimmer platform*. Shimmer is designed specifically for wearable applications and is used widely in medical fields. Much of Shimmer's resources are open source, making it useful to the goal of that protocol.

Shimmer's sensors are separated into three groups including *kinematic sensors, biophysical sensors,* and *ambient sensors*. Kinematic sensors record movement (i.e. velocity and position), biomedical sensors record medical data (i.e. heart rate and body temperature), and ambient sensors measure environmental properties (i.e. temperature and humidity). Shimmer comes with the following sensor options: ECG, EMG, GSR, 9DoF, GPS, Strain Gauge, and Accelerometer. Shimmer also includes Lab View, Matlab, Android, and Windows applications as basestation platforms [12]. For the OS platform, Shimmer's motes are TinyOS based. The implementers of the BAN used TinyOS because it's a well used library that's been around for a long time and has a large support community [1].

The protocol itself is very good for generic use. The mote has six states*: Idle, Discoverable, Paired, Connected, Command & Inquiry and Streaming*. The Basestation, on the other hand has a total of seven states: *Idle, Discovery, Paired, Connected, Command & Inquiry, Mote Data* and *Mote Response*. As a general summary, the BAN is designed using a state machine design pattern. Each state has one action. Some states allow a user to send commands, request sensor data, receive sensor data, etc. Doing a different task means transitioning to a different state. The protocol specifically forbids doing or requesting an action for a state other than the one the mote is currently in [1]. The way this is implemented is through a set of functions that allows the basestation to ask each mote that connects how to use it. This allows the motes to teach the basestation all of its functionality. Thus, the basestation has no prior knowledge of what any of the motes can do. There are only 7 different kinds of messages in the BAN protocol, they are detailed in Figure 7:

0	1	2	3	4	5	6	7	MSG ID
0	0	0	0	0	0	0	0	Mote Data
0	0	0	0	0	0	0	1	Sensor Inquiry
0	0	0	0	0	0	1	0	Command Inquiry
0	0	0	0	0	0	1	1	Command Params Inquiry
0	0	0	0	0	1	0	0	Command Returns Inquiry
0	0	0	0	0	1	0	1	Data Inquiry
								Not Used
								...
								Not Used
1	1	1	1	1	1	1	1	BaseStation Learned Command

Figure 7: Types of Messages in BAN Protocol

This means that the BAN is completely extendable to include different motes without updating the basestation. The unused message types allow the protocol itself to be extended as well. Figure 8 illustrates the communication architecture of the BAN.

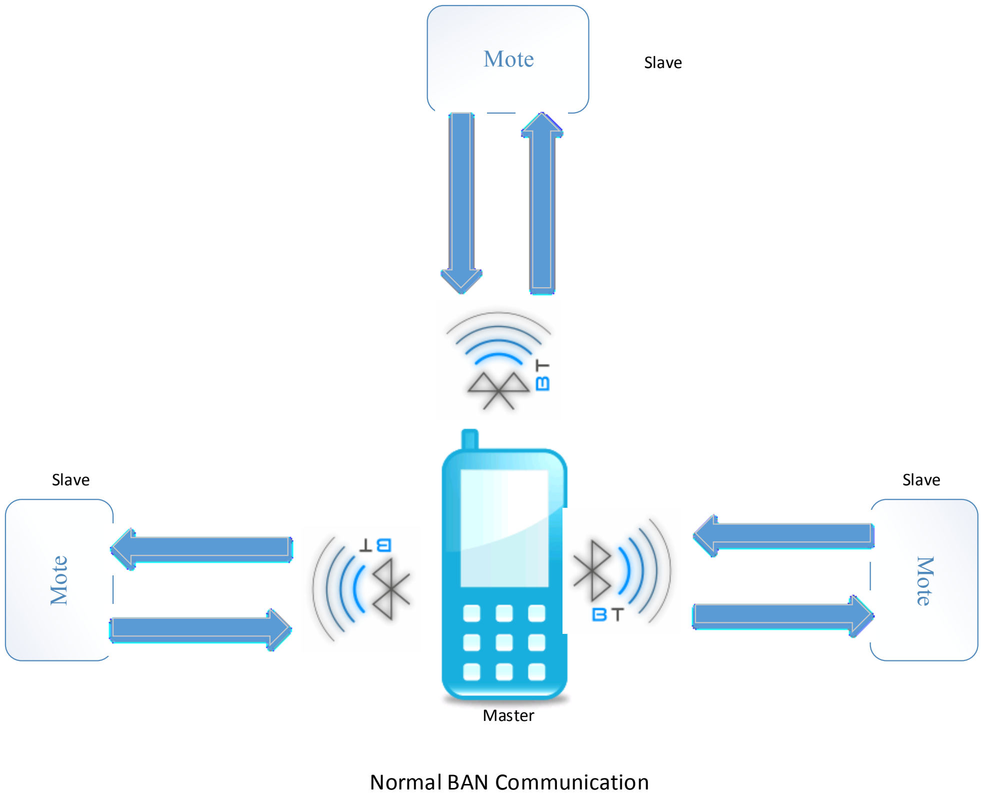


Figure 8: BAN Communication Overview

6.2 Threat Model

In addition to the protocol there are a few more assumptions. One assumption is that the basestation user is not the attacker as a BSN can contain important medical devices. The basestation can only pair with motes when the user initiates pairing. It is assumed that the user will not knowingly pair with any attacker. In addition to the system here, there are assumptions made about an attacker.

There is an assumption that the attacker would have relatively high computational abilities – in addition to the computational power of today's high end laptops it is relatively cheap and simple to rent out compute time on servers from companies like Amazon. Specifically *Amazon Web Services* has the *Amazon Elastic Compute Cloud (Amazon EC2)*, which gives 750 computing hours on Linux and 750 hours on Windows server free then charges $0.105 (2 Cores and 3.75 GiB RAM) to $1.68 an hour (32 cores and 60 GiB RAM) for compute time on compute optimized servers [28]. The attacker can also spoof, launch man in the middle attacks, and has the knowledge to decrypt encryption. Decrypting encryption is where the attacker would most benefit from EC2 as EC2 is made for relatively short (hours, days, or months) and intense workloads. With the short range of Bluetooth, only one adversary was assumed; however one person can use multiple devices simulating multiple adversaries. This project did not use Amazon EC2 to simulate the attacker. It is used here as an example of where an attacker can rent out heavy duty compute space to crack encryption.

7 Wearable Honeypot

The Wearable Honeypot system is meant to detect threats to a BSN. The basis for the honeypot is a message system to attract attackers to the honeypot. The message system involves a message exchange between the BS and specialized helper motes. The BS and the motes communicate in a pre-arranged way. This message exchange acts as bait for an attacker to pay attention to the helper motes because it is the most active part of the BAN. Initially just like with other motes, the basestation will ask for all information about the motes (sensors, types of data, commands, etc.) and then initialize the honeypot message system. In this mode the BS periodically sets and resets what the motes are sending to it. The data the mote sends back is coordinated and known to the basestation. An attacker spoofing messages would cause the expectations of this system to be violated. Using this approach many attacks can be detected. The architecture of the honeypot is shown in Figure 9.

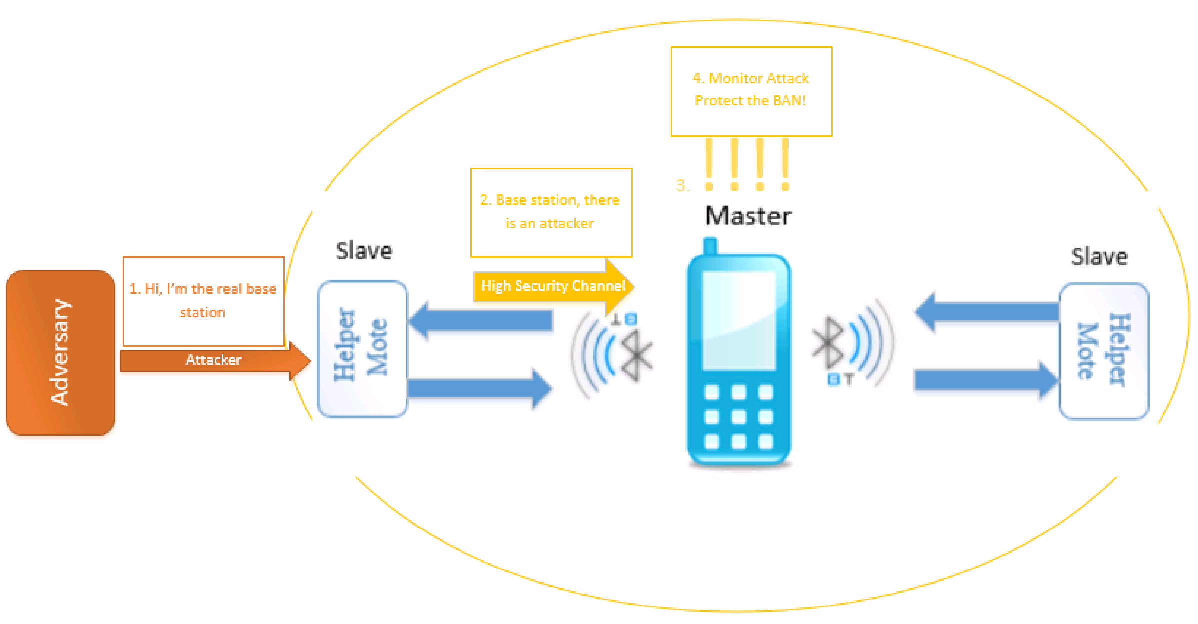


Figure 9: Wearable Honeypot Architecture

Because a honeypot is meant to detect threats, as a first step in designing the honeypot system, a *threat model* was developed. The threat model was an outline of all possible adversary attacks the honeypot will be on the lookout for. By examining the Bluetooth protocol and BAN protocol, attacks were devised. This eventually became a *honeypot model* when corresponding detection information was added. However, before that is presented, it is important to understand message system because the honeypot model depends on it.

7.1 Attacker Attraction Message System

As mentioned above, the detection mechanisms depend on a *message coordination scheme*. There are two *logical communication channels* between the helper motes and the basestation, a *high security channel* and a *low security channel*. The high security channel is where the message system is coordinated by the basestation and the low security channel is for "normal" BAN PnP communication. The high security channel is secured with the *AES block cipher* in *cipher block chaining (CBC)* mode. This message coordination scheme relies on simultaneously synthesizing accelerometer data on the motes and BS, which involves a *PRNG (Pseudo-random Number Generator)*. Over the high security channel, the basestation sends a coordination message which tells the motes which kind of accelerometer data (sitting or walking) to synthesize and how many data points to send back to the basestation as supposed sensor data for accelerometers. This way, the basestation can know what messages to expect from motes and when (these stream in and the average rate is monitored for sudden changes). Additionally, once a mote receives a coordination message, it should only ever expect more of them and nothing else. If a mote receives any other message it will send an encrypted message to the basestation indicating that an attacker was detected. If the basestation receives any packets from helper motes before they request data stream to be started, then this also allows attackers to be detected. Table 1 presents packet description of the coordination message and an example mote return packets. The basestation *coordination message* packet is broken down into two parts: Header and Body. The header specifies the packet size, sequence number and Message ID (1111 1110b). The body specifies the type and the number of accelerometer values to send as well as initializes the PRNG. The mote packet response also contains a header and body where the header specifies packet size, sequence number and message ID while the body specifies Sensor ID and message value.

Table 1: Honeypot Message System Specification

<table>
<tr><th colspan="2">Honeypot Message System Specification</th></tr>
<tr><td>BS Coordination Message</td><td>Example Mote "DATA" Response Packets</td></tr>
<tr><td rowspan="3">// Header:
0000 0000
0001 1000 : packet size 24
0000 0000
0000 0111 : sequence number
1111 1110 : message ID
// Body
// 10 messages -- array of 10 16 bit values
0000 0001 : // Type of data, 1 for walking, 0 for sitting
0000 0010
1101 0000 : // Number of data points to send
// 4 32 bit integers to initialize PRNG
0000 0011
0100 0111
0101 0000
0101 0011 : 1
0000 0000
0110 0011
0111 0111
0010 1010 : 2
0011 1001
0110 0000
0000 0011
0110 0100 : 3
1010 0101
0111 0111
0111 1000
0000 0100 : 4</td><td>// First mote response
// Header:
0000 0000
0000 1000 : packet size 8
0000 0000
0000 1000 : sequence number
0000 0000 : message ID - mote data
// Body:
0000 0001 : Sensor ID
0110 0011
0100 0010 : Sensor data payload (message value)</td></tr>
<tr><td>// Second mote response
// Header:
0000 0000
0000 1000 : packet size 8
0000 0000
0000 1001 : sequence number
0000 0000 : message ID - mote data
// Body:
0000 0001 : Sensor ID
0110 0000
0000 0011: Sensor data payload (message value)</td></tr>
<tr><td>// Third mote response
// Header:
0000 0000
0000 1000 : packet size 8
0000 0000
0000 1010 : sequence number
0000 0000 : message ID - mote data
// Body:
0000 0001 : Sensor ID
0100 0111
0101 0000: Sensor data payload (message value)</td></tr>
</table>

In a situation where an attacker is detected, the message ID would alter to 1111 1101b and transmit this sequence over the secure channel. With this communication mechanism, the basestation will know when it wasn't a honeypot mote that sent the message.

7.1.1 Synthesizing Accelerometer Data

For the message system, we needed to determine a method to send false yet realistic data to attract the attacker's attention yet not make it obviously fake. The idea we set upon was to synthesize real sensor data. We settled on accelerometer data as the best option for this endeavor. There are many devices with accelerometers and it isn't abnormal for someone to have more than one sensor monitoring accelerometer data. After that, exactly how we synthesize it became the next issue. Mathematically synthesizing the data is very computationally intensive, so we decided to start with a real data bank of accelerometer values for different activities.

7.1.1.1 Real Accelerometer Data

We found data collected and published for the purpose of activity recognition from accelerometer data[29]. The activities were separated, graphed, and the standard deviations were calculated in order to understand the data. The Wearable Honeypot is kept simple and uses two main activities and two more as transitions between them. Walking and sitting are the main activities. When transitioning from sitting to walking, one must first stand up from sitting, which we have data for; when going from walking to sitting, one must sit down first. These provide a couple seconds of realistic transition. There were more activities available (such as lying down, on all fours and falling), however these activities that don't generally happen in public. The graph in Figure 10 present the data points for walking.

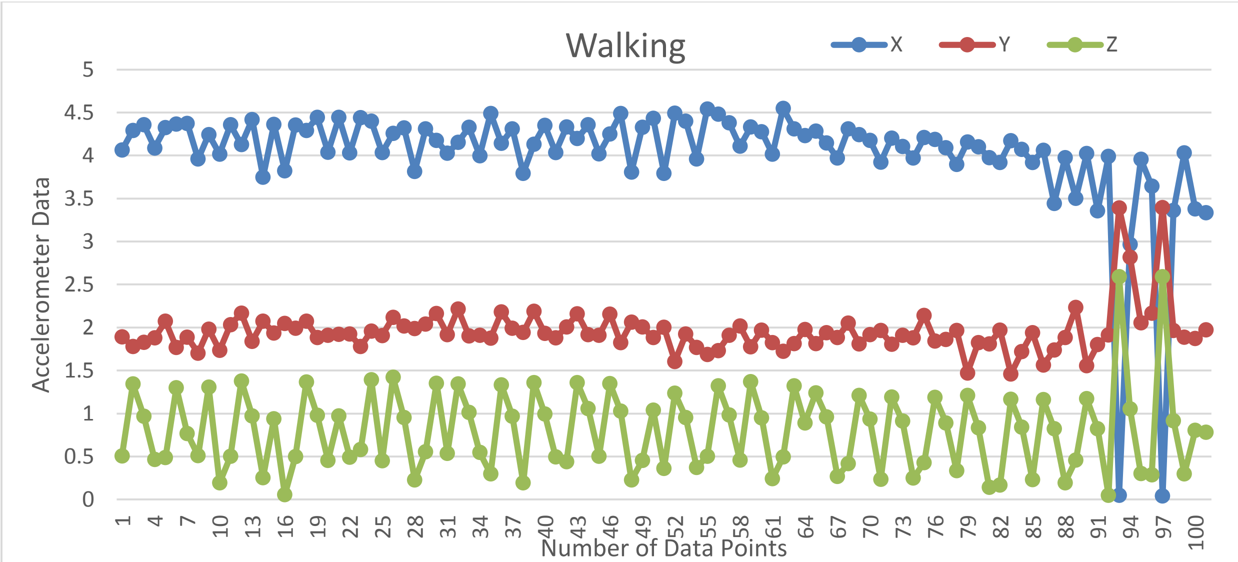


Figure 10: Original Walking Accelerometer Data

Figure 10 shows a fairly consistent data set of walking accelerometer values. Towards the end it appears that the user may have been transitioning to another activity because it doesn't match the general pattern in the rest of the data. While calculating the standard deviation these values were ignored.

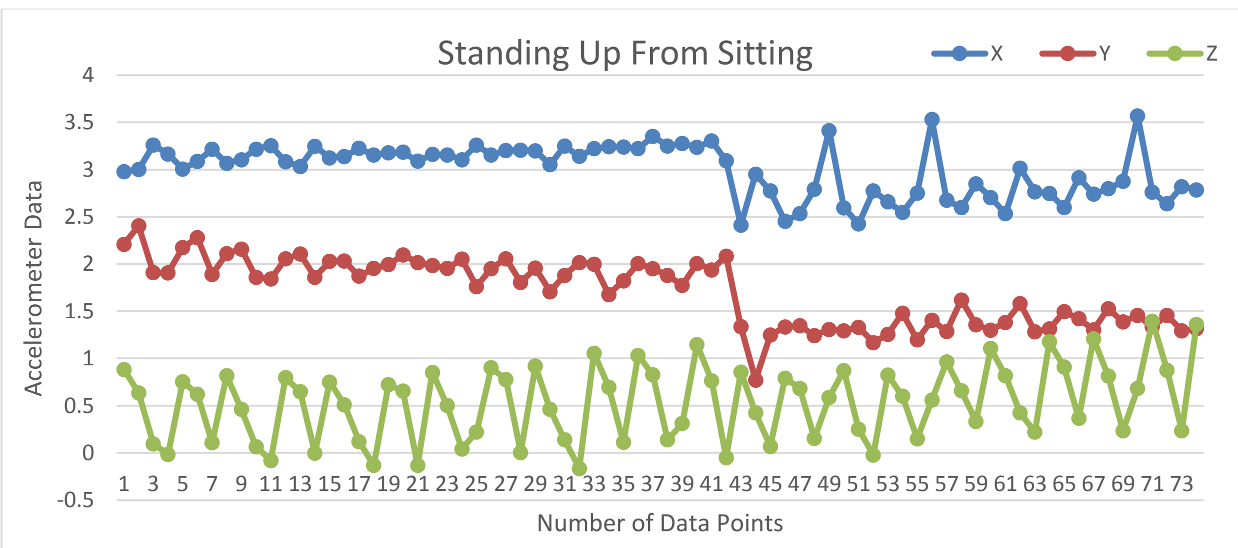


Figure 11: Original Standing Up From Sitting Accelerometer Data

Figure 11 shows accelerometer values for standing up from sitting. The data in this section is fairly regular between points, however a little past halfway through there is a major shift downward for the X and Y. From that point on it is fairly regular again. To accommodate for this, the graph was divided in two and two different standard deviations were calculated.

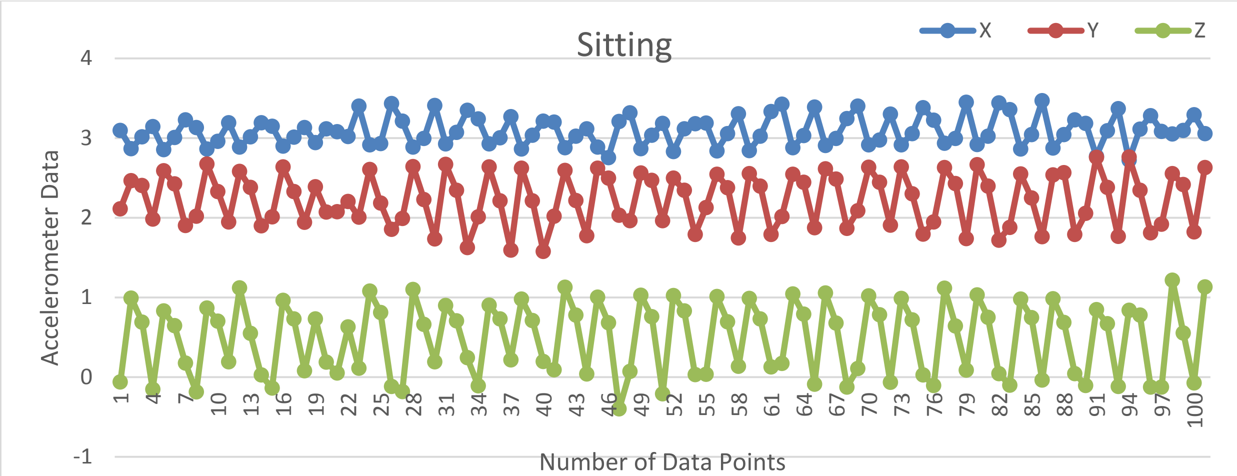


Figure 12: Original Sitting Accelerometer Data

Figure 12 shows the accelerometer data from sitting. As would be expected it is very regular.

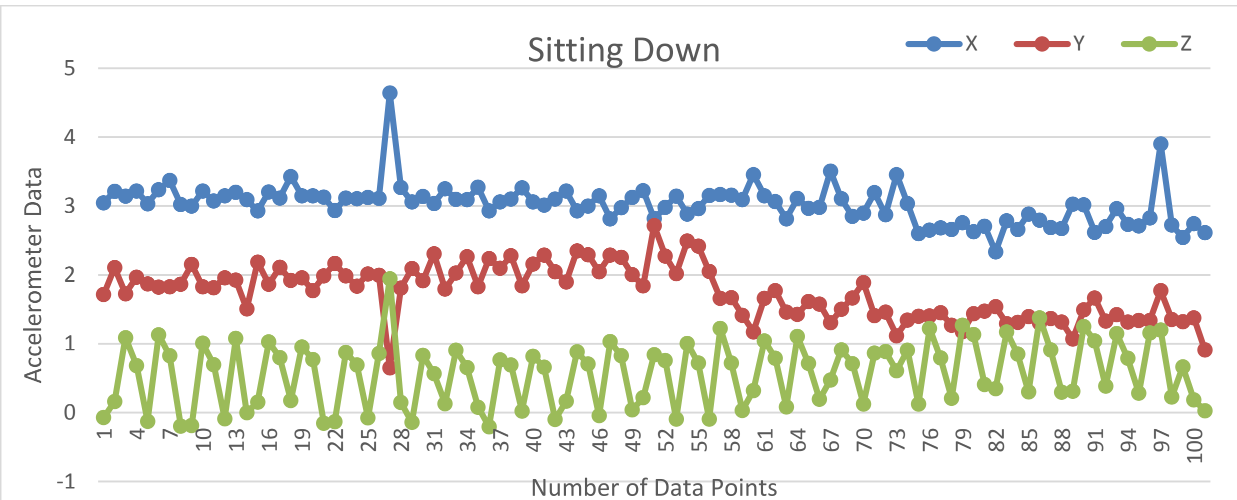


Figure 13: Original Sitting Down Accelerometer Data

Figure 13 shows the sitting down data. Due to the Y vector presenting a similar problem to standing up from sitting down, all vectors were divided in two and two separate calculations were made for both range and standard deviation. The smallest range and standard deviation values for each vector were used for future calculations. Table 2 presents each activity's vector and their standard deviations.

Table 2: Standard Deviation

Activity	Vector	Standard Deviation
Walking	X	0.272615
	Y	0.151893
	Z	0.407375
Standing Up From Sitting	X	0.149059089
	Y	0.109661235
	Z	0.407219629
Sitting	X	0.185340687
	Y	0.326012929
	Z	0.450997835
Sitting Down	X	0.221174625
	Y	0.363783609
	Z	0.443966194

As one may notice, if we simply replay this data over and over, it would become obvious that it is fake. There are some areas where data points are exaggerated. These would be most obvious. However we interpreted those data values as noise when the test subject transitioned from one activity to another. Using this assumption those values were ignored for the calculation of the standard deviation for each dataset. However, even without the spikes, transmitting the same values every 100 or so points will be obviously fake anyway. Therefore we need to modify this data.

7.1.1.2 Pseudo-random Number Generator Selection

Initializing the PRNG requires determining a method to randomize the accelerometer data. Several PRNG's were researched; three in particular: RC4, Mersenne Twister and TinyMT. Since the quality of randomness wasn't as important as minimized computational load and maximizing battery efficiency, first an analysis of the number of operations (assignment, arithmetic operations, bitwise operations such as & and bit shift) required to generate random numbers as shown in Table 3:

Table 3: PRNG Operation Comparison Table

Attribute	RC4 [31]	Mersenne Twister [32]	TinyMT [30]
State Memory Size	256 Byte + 40 Byte key	2496 Bytes	16 bytes
Operations until 1st number	206 + 2844 = 3050	4364 + 8112 + 20 + 1 = 12478	101 + 41 = 142

Operations Until 2nd Number	3050 + 2844 = 5894	12478 + 20 = 12498	142 + 41 = 183
Operations until Nth number	206 + 2844N +⌊(N/40)⌋*204	4364 + 8112 + 20N + 1 + ⌊(N/624)⌋*8112	101 + 41N

As you can see, the TinyMT PRNG is a clear choice given those criterion. Additionally it is also of high quality. It has a period of 2^{127}, and the floating point numbers are based upon evenly distributed 32 bit integers[30]. Pseudo-code or implementations for each is included in the appendix. Using TinyMT, we can add small random offsets to the original Data.

7.1.1.3 Modified Accelerometer Data

Utilizing the TinyMT PRNG as well as the calculated standard deviations of each activity's vector, multiple randomized number is tempered to within +- one standard deviation. TinyMT can return a floating point r such that 0 <= r < 1. Equation 1 can be used to temper r to the desired range.

$$r` = (r - 0.5) * std * 2$$

Equation 1

Where std is the standard deviation and r` is the tempered result.

These tempered offsets were then added to the original dataset creating a randomized, realistically synthesized set of data. The random offsets were needed so the same data wouldn't be streamed over and over, and the spikes (noise) needed to be removed because a spike every constant number of data points is also suspicious. The graph presented in Figure 14 shows the original walking vector (as in the magnitude of the x, y, and z), the noise cancelled vector using the criteria described above, and the resultant randomized vector.

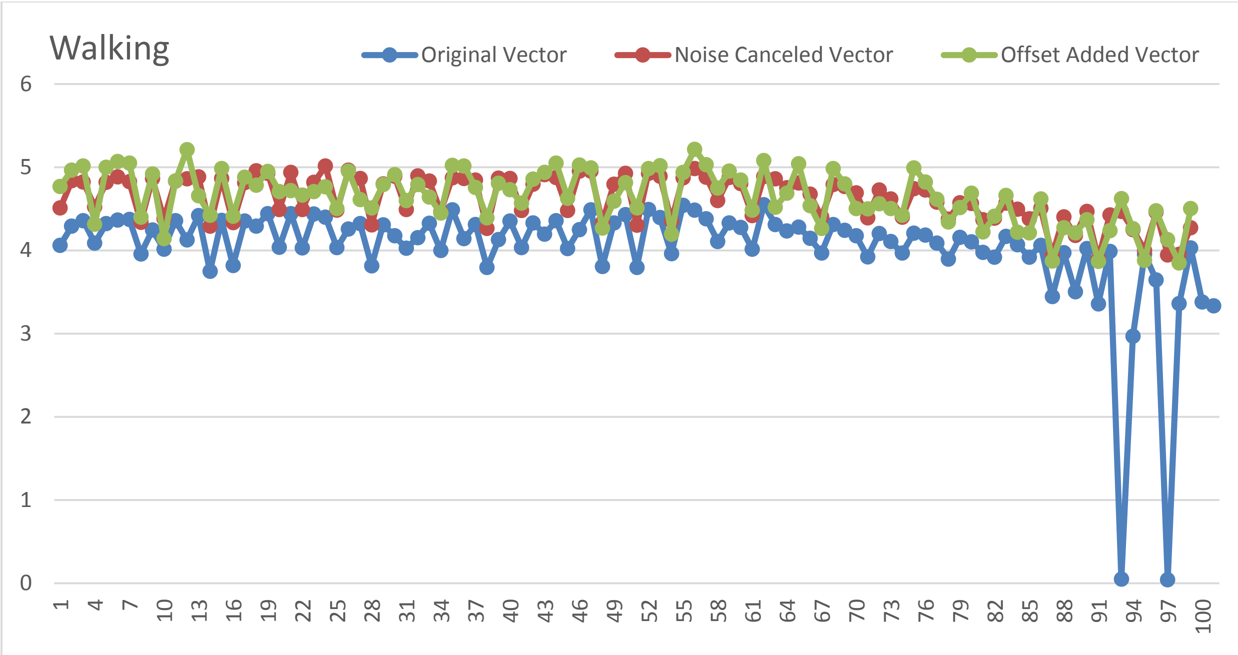


Figure 14- Modified Walking Accelerometer Data

The resultant offset vector has more or less the same pattern as the original data, however is clearly different than the original data. Meaning that this is plausibly walking data, and it never repeats. Figure 15 shows the same vectors as Figure 14 for standing up from sitting.

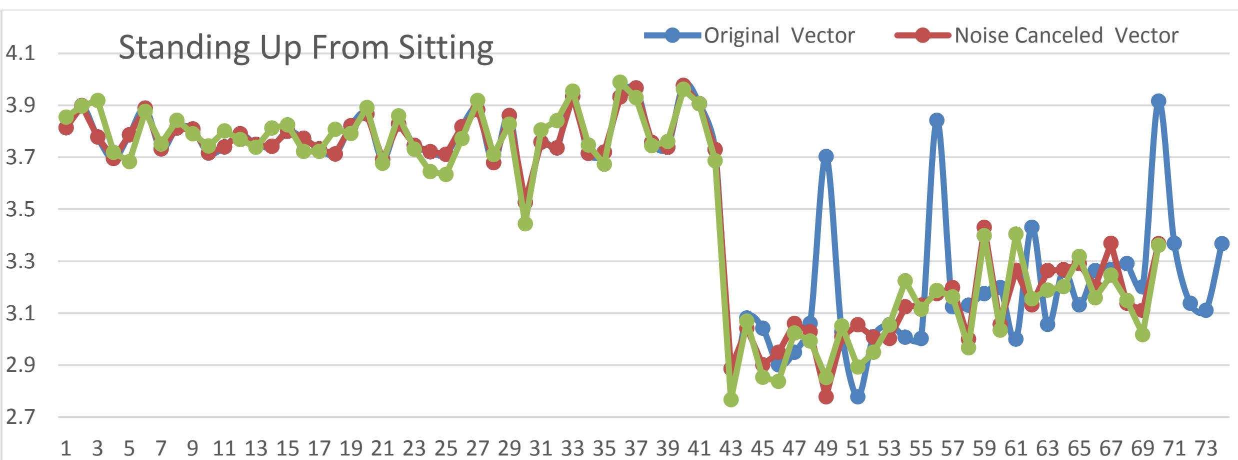


Figure 15: Modified Standing Up Form Sitting Accelerometer Data

Like before the resultant offset vector is clearly the same type of accelerometer data, however the data values aren't the same and don't repeat. Figure 16 shows the same vectors as Figure 14 for standing up from sitting.

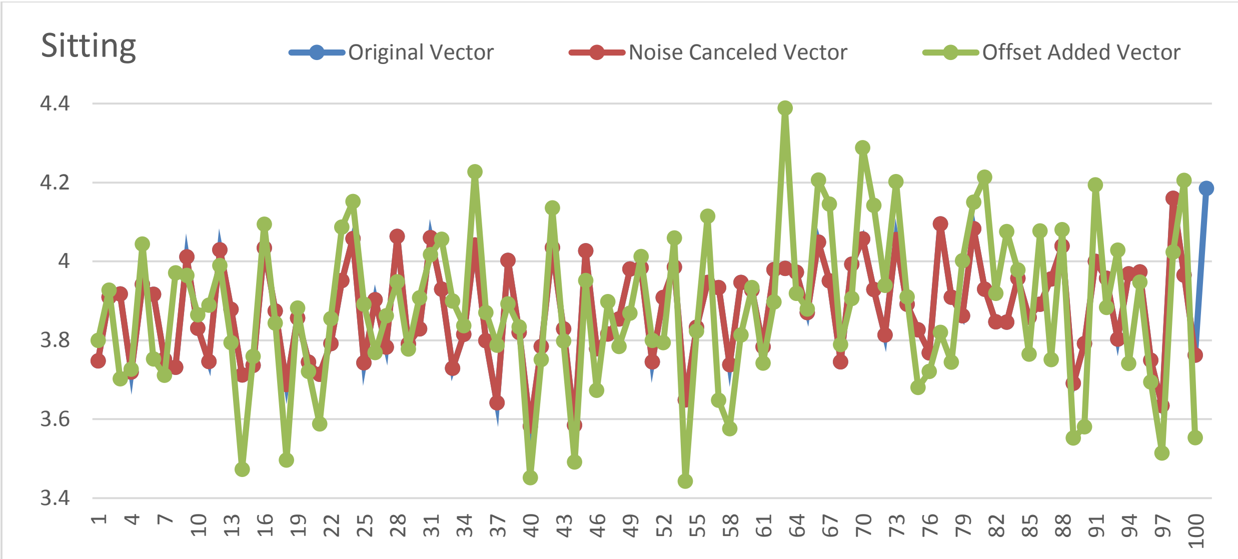


Figure 16: Modified Sitting Accelerometer Data

The sitting vector is very close, as the regular pattern from the original graph would suggest. This zoomed in graph very tightly follows the original line (in most places, what looks like a spike resulted from 3 offsets for X, Y and Z that were very closed to +standard deviation). This very plausibly provides sitting data that doesn't repeat. Figure 17 shows the same vectors as Figure 14 for standing up from sitting.

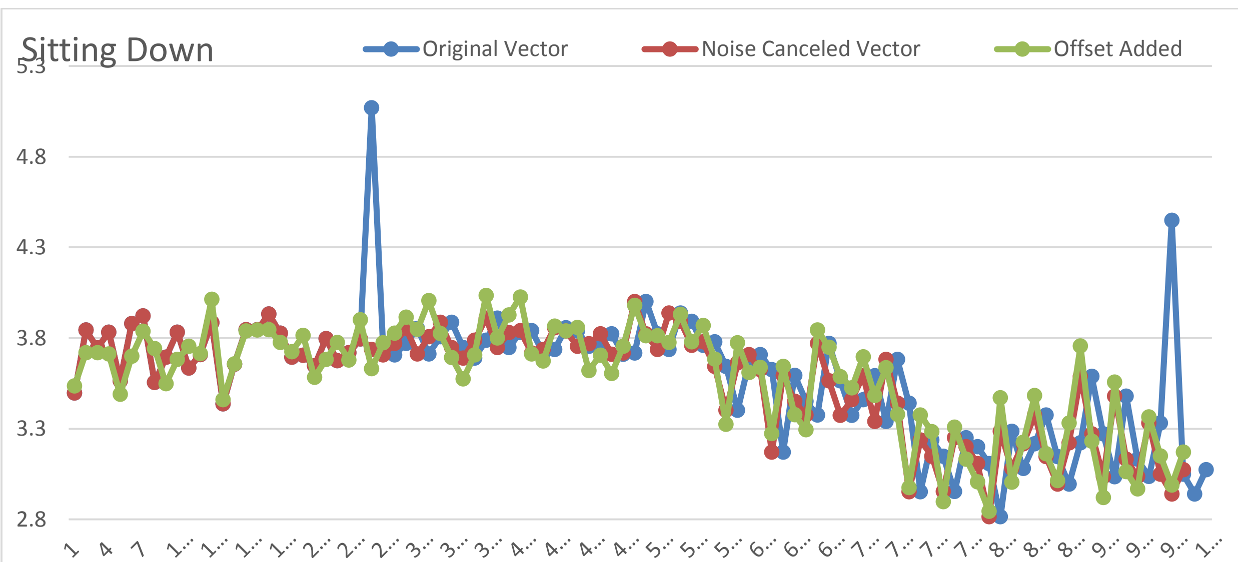


Figure 17: Modified Sitting Down Accelerometer Data

With this graph we can conclude the offset vector does not repeat and stays consistent and in range within the actual activity for all activities.

7.1.2 Message Window

Going message by message and monitoring message by message delays doesn't result in a very robust detection mechanism and would be prone to many false positives and false negatives. This is because if one packet is dropped, that is a sign there may be an attacker. There are also many attacks that would be missed. Instead of worrying about each message individually a message window is considered.

For the message window there is a balance of keeping track of more messages and therefore having more information in which to build detection mechanisms from and having fewer messages in the window allowing for faster detection. The mote tries to send the accelerometer data value every 250ms.

In a message window, we also have to consider the possibility of packets being lost due to some temporary interference. With a message window of size n, k number of packets need to be dropped before the basestation determines this to be an attacker. If we have a small window size n and a small k, the speed at which an attacker can be detected increases. For instance, to allow 4 packets to be dropped a window of 8 messages minimum would be needed, to be safe use a 10 message window.

Using this 10 message window, if 4 packets were dropped, the system would know what that 5^{th} packet is supposed to be when it comes in. For the purposes of the *Wearable Honeypot* 4 packets in a row are acceptable, but the 5^{th} one would mean there is an attacker. Figure 18 demonstrates this idea.

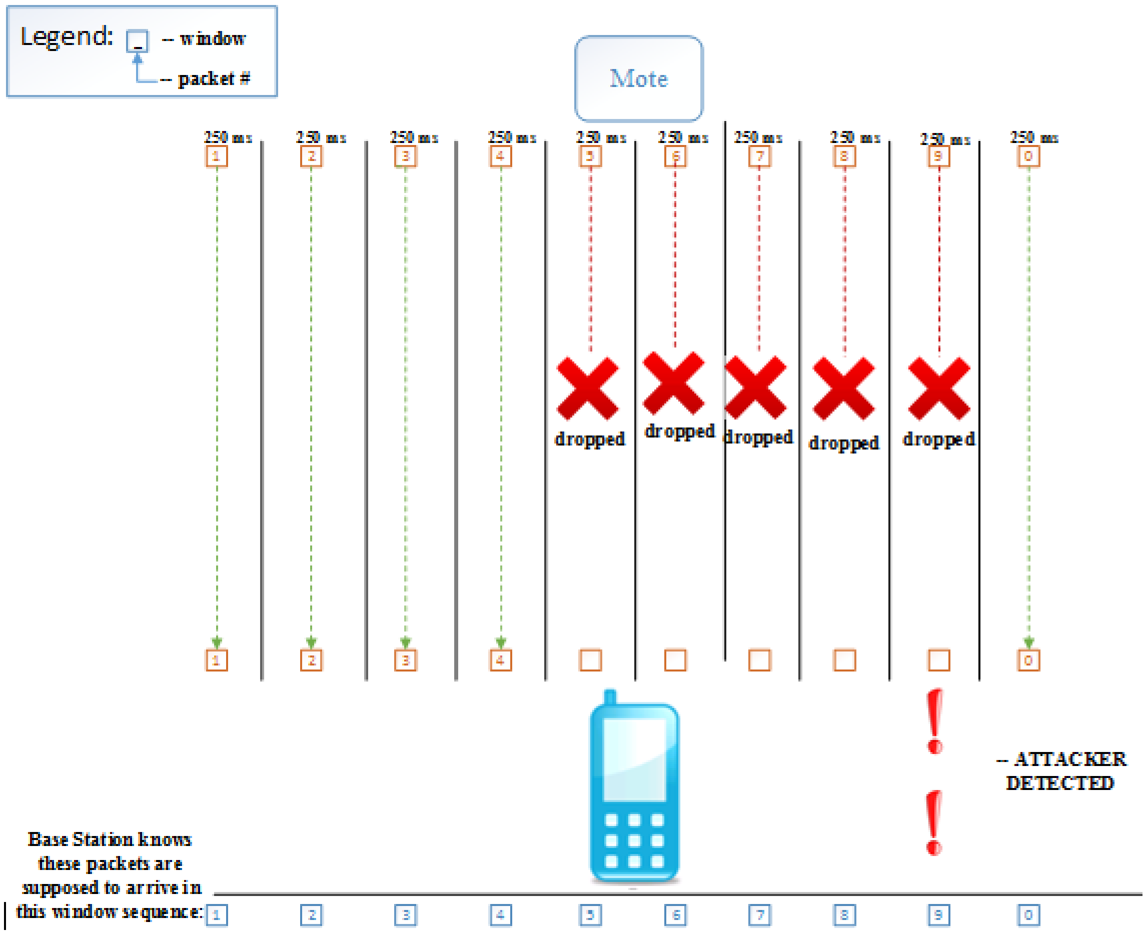


Figure 18 - Five Packets Dropped in A Row

This message window also protects from replay attacks, as the expected value is known, so an attacker cannot resend an old one. Within the message window the average delay is kept track of. If, within a window, the average delay get too far from 250ms, then an attacker would be detected. If packets are dropped, the expected delays for the missing packets are taken out from that delay. The attacker has a small chance spoofing an expected value in the window (1/4096 – the incoming value is a 12-bit ADC reading from an accelerometer). If, by chance, the attacker manages the expected packet, then there is no way of detecting this. But, if the attacker sends an unexpected packet, then an attacker would be detected. Figure 19 demonstrates this idea.

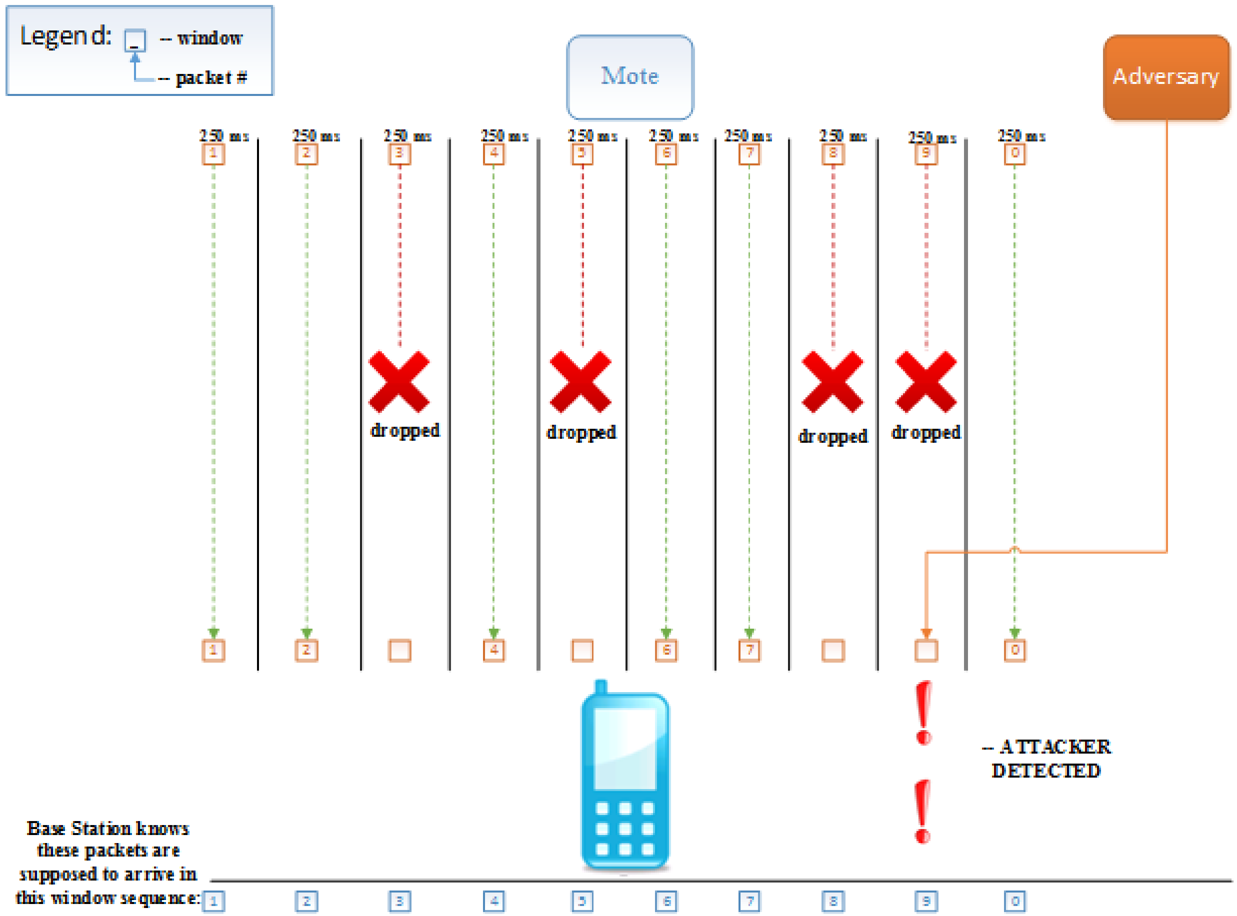


Figure 19 - Attacker Window Insertion

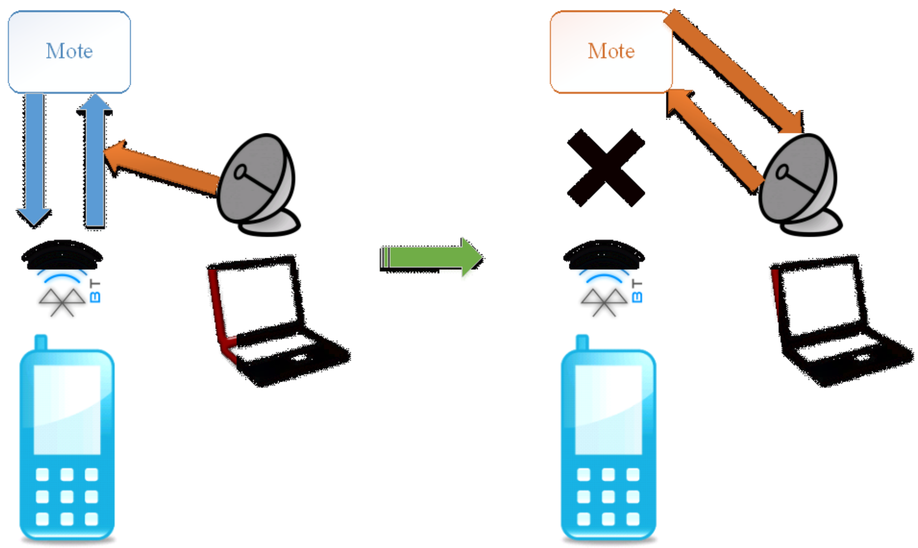
In this situation, while the real packet may have been dropped (so the spoofed packet wouldn't be caught on the basis of delays) the spoofed packet would then be compared with the expected message and the attacker would be detected.

7.2 Honeypot Detection Mechanisms

The Honeypot started threat model; to determine the detection mechanisms required, first the attacks to detect had to be known. First, the Bluetooth protocol itself was examined. This yielded many attacks (mostly *disconnection attacks*) without any consideration of the BAN protocol. Then when it came to the BAN protocol itself, there were two main attack scenarios – *spoofing the basestation* and *spoofing a mote already in the BAN*. Given the master slave nature of Bluetooth one cannot spoof a new mote and try to add it to the BAN, so attacks of this principle were not considered.

7.2.1 Bluetooth & Disconnection Attacks

The Bluetooth protocol yields many attacks involving disconnecting the basestation from the motes. Doing this would limit the amount of communication and leave the motes vulnerable and able to be completely hijacked, i.e. disconnected from basestation. Then the attacker then has the ability to pair with the mote and become its new master. The illustration in Figure 20 presents a visual explanation of this type of attack.



Attacker unpairs mote and pairs mote to itself

Figure 20: Disconnection Attack

Table 4 details the different types of disconnection attacks with a detailed description of how these attacks would look like. The chart also presents the methods of detecting these attacks.

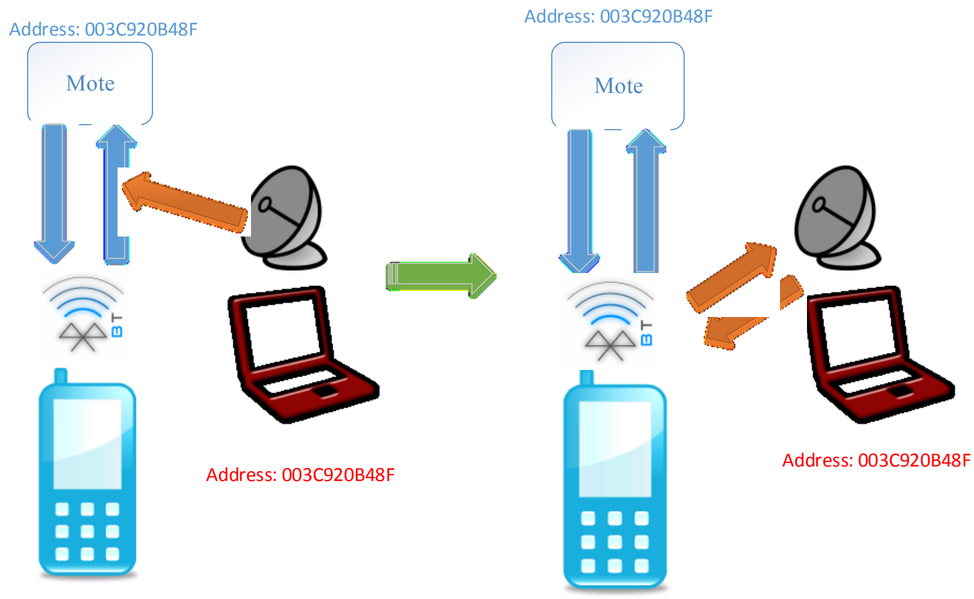
Table 4: Bluetooth and Disconnection Attacks

Bluetooth and Disconnection Attacks (Type C)		
Description of Attack Vectors	Application Packet/Modifications to BT Frame	Detection Mechanism
Attacker: Spoofed Mote/Spoofed Basestation Target: Motes/Basestation 1. Bluetooth eavesdropping. Especially moment of pairing will compromise all Bluetooth level security.	Best done with a Bluetooth sniffing device like Ubertooth[24]. However, BT addresses are not actually globally unique which means you can iterate through the common address and find a non-discoverable device [22].	There is generally no way to detect eavesdropping.

<table>
<tr>
<td>
<table>
<tr><th>Attacker</th><th>Target</th></tr>
<tr><td>Spoofed Mote/Basestation/Other</td><td>Connected Bluetooth devices in BAN</td></tr>
</table>
2. An attack that jams all the Bluetooth channels will cause Bluetooth devices to think they're disconnected and re-initiate the pairing process. [22]
</td>
<td>This is done by sending signals on all available Bluetooth frequencies. When devices re-initiate pairing, an attacker can pose as both the basestation and motes and have legitimate parties connect to the attacker spoofs [22]. Thus giving a true MIMA.</td>
<td>Whenever a Bluetooth device disconnects from a basestation, its address and the time it disconnected is stored in a shared data structure. If there are only 2 motes and they disconnect within 1 sec or else if all the motes disconnected within 2 seconds, an attack is detected.</td>
</tr>
<tr>
<td>
<table>
<tr><th>Attacker</th><th>Target</th></tr>
<tr><td>Spoofed Basestation</td><td>Motes in BAN</td></tr>
</table>
3. An attack that sends pairing request packets over and over without follow up.
</td>
<td>After entering a PIN, a number is generated and sent to the slave device to initiate the pairing process. Instantiate packet and send.</td>
<td>With the default Bluetooth library on Android you can't access the part of the Bluetooth stack to detect this.</td>
</tr>
<tr>
<td>
<table>
<tr><th>Attacker</th><th>Target</th></tr>
<tr><td>Spoofed Motes</td><td>BaseStation</td></tr>
</table>
4. Buffer overrun on the Bluetooth frame. This can overrun the Bluetooth receive buffer causing the app to crash.
</td>
<td>Using Ubertooth inject a packet that gives the wrong size in a Bluetooth frame [24].</td>
<td>With the default Bluetooth library on Android you can't access the part of the Bluetooth stack to detect this. The default library was once vulnerable to this kind of attack but a bug fix was merged into the Git repository in 2013. [25]</td>
</tr>
</table>

7.2.3 Targeting BS by Spoofing Motes

The second kind of adversary could be an attacker that is pretending to be a mote already in the BAN. One reason an attacker may want to do this is to confuse the basestation and send false information around. This may cause behavior in the BAN that would be detrimental to the user. The illustration in Figure 21 presents a visual representation of this kind of attack.



Attacker spoof mote responses

Figure 21: Spoofed Mote Attacks

Table 5 outlines different attacks based on spoofing motes and their detection mechanisms.

Table 5: Spoofing Motes Already In Ban

Spoofing Motes Already in BAN (Type B)		
Description of Attack Vectors	Application Packet/Modifications to BT Frame	Detection Mechanism
Attacker: Spoofed Mote; Target: Basestation 1. Buffer overrun attack on the application packet. This means the Bluetooth layer would be unaffected, but when the application packet gets handed up it will be bigger than the application expected and this can overrun the buffer allowing malicious code to be inserted in adjacent memory to that used by the app.	Header: 0000 0000 0001 0110 ; packet size 22 0000 0000 0000 0111 ; sequence number 0000 0101 ; message ID Body 0000 0001 ; sensor ID Value mappings: 0000 0011 : Size 0000 0010 : type ID 2's comp integer 0000 0000 0000 0011 ; size of value name 0100 0111 ; G 0101 0000 ; P 0101 0011 ; s 0000 0000 0000 0011 ; SIZE OF equation 0111 0111 ; x 0010 1010 ; * 0011 1001 ; 9 0000 0000 0000 0011 ; size of value units	The size of the messages are known therefore any spoofed message that is oversized would be easily detectable.

<table>
<tr><td></td><td>0110 0100 ; d
0110 0101 ; e
0110 0111 ; g
0000 0000 ; null pointer beyond buffer, byte 23
0000 0000
0000 0000
0000 0000</td><td></td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Motes</td><td>Basestation</td></tr></table>2. Spoof Data Inquiry response packets, i.e. try giving data conversion equations that divide by 0.</td><td>Header:
0000 0000
0001 0110 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0101 ; message ID
Body:
0000 0001 ; sensor ID
Value mappings:
0000 0011 : Size
0000 0010 : type ID 2's comp integer
0000 0000
0000 0011 ; size of value name
0100 0111 ; G
0101 0000 ; P
0101 0011 ; S
0000 0000
0000 0011 ; SIZE OF conversion equation
0111 0111 ; x
0010 1111 ; /
0011 0000 ; 0 – conversion equation
0000 0000
0000 0011 ; size of value units
0110 0100 ; d
0110 0101 ; e
0110 0111 ; g</td><td>Cleanse input and conversion equations. As part of cleansing the conversion equations make sure to check divide by 0 and anything besides a mathematical expression.</td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Motes</td><td>Basestation</td></tr></table>3. Too many packets can make it so a basestation is too busy processing incoming packets to control mote. DOS attacks such as this are known to drain battery life significantly. [22]</td><td>It doesn't really matter what is in the packets themselves. It may be a good idea to spoof source address in the Bluetooth frame, but that's not necessary for the attack.</td><td>Two packets received in less than the expected delay is obviously an attacker because coordinated messages only come every previously coordinated number of milliseconds.</td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Motes</td><td>Basestation</td></tr></table>4. Attacker transmits a message of type Mote Data sending data that is not plausible. This may cause bad information to be recorded by the Basestation.</td><td>0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0000 ; message ID
0000 0001; sensor ID
1111 1111 ;
1111 1111; sensor data payload</td><td>With the content of the messages known, any such message coming in with a different value would be from an attacker.</td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Motes</td><td>Basestation</td></tr></table>5. Attacker transmits a message of type Mote Data sending data that is plausibly correct. This will cause plausibly incorrect information to be recorded by the BAN</td><td>0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0000 ; message ID
0000 0001; sensor ID
0000 0000
1010 1111; sensor data payload</td><td>With the content of the messages known, any such message coming in with a different value would be from an attacker.</td></tr>
</table>

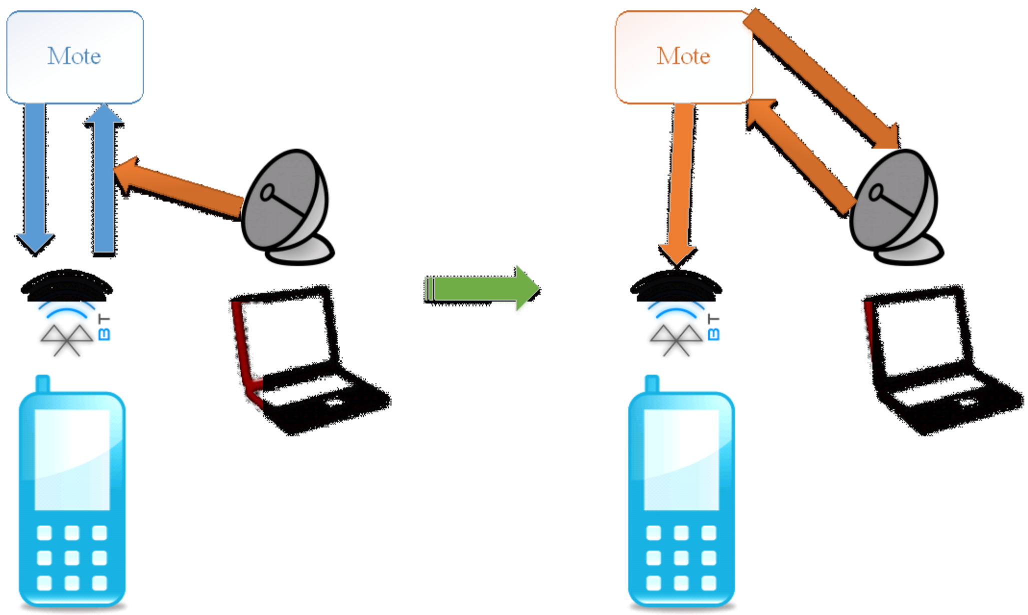
<table>
<tr><td>which can have differing consequences depending on the device.</td><td></td><td></td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Mote</td><td>Basestation</td></tr></table>6. Spoof packets with incrementing sequence numbers in header so basestation and mote’s sequence numbers become out of sync</td><td>Packet 1:
0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0000 ; message ID
0000 0001; sensor ID
0000 0000
1010 1111; sensor data payload
Packet 2:
0000 0000
0000 1000 ; packet size
0000 0000
0000 1000 ; sequence number
0000 0000 ; message ID
0000 0001 ; sensor ID
0000 0001
1010 1110; sensor data payload
Packet 3:
0000 0000
0000 1000 ; packet size
0000 0000
0000 1001 ; sequence number
0000 0000 ; message ID
0000 0001 ; sensor ID
0000 0001
1010 1111 ; sensor data payload</td><td>In the basestation implementation they throw out the sequence number. Documentation says otherwise. Therefore this needs to be detected (by keeping track of incoming sequence numbers).</td></tr>
<tr><td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Mote</td><td>Basestation</td></tr></table>7. Spoof a mote response to a Sensor Inquiry. Giving false information about available sensors will cause the BAN to malfunction.</td><td>Packet 1:
Header
0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0001 ; message ID
Body:
0000 0001: number of Sensors
Sensory mappings:
0000 0001 : sensor ID
0000 0011 :
0000 0010 : size of sensor name
0000 0000
0000 0100 : size of value name
0100 0111 : G
0101 1001 : Y
0101 0010 : R
0100 1111 : O - sensory name</td><td>The basestation will know what the helper mote's response is supposed to be. If it differs an attack is detected.</td></tr>
</table>

<table>
<tr>
<td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Mote</td><td>Basestation</td></tr></table>8. Spoof a Command Inquiry response packet.</td>
<td>Packet 1:
Header
0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0010 ; message ID
0000 0000 : sensor ID 0 for general request
0000 0001 : number of commands
//Command mappings
0000 0001 : command ID
0000 0000 :
0000 0100 : size of command name
0101 0011 : S
0101 1001 : Y
0100 1110 : N
0100 0011 : C – command name</td>
<td>The basestation will know what the helper mote's response is supposed to be. If it differs an attack is detected.</td>
</tr>
<tr>
<td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Mote</td><td>Basestation</td></tr></table>9. Spoof a Command Returns Inquiry response packet. Divide by 0 attacks or other false info.</td>
<td>Packet 1:
Header
0000 0000
0000 1000 : packet size
0000 0000
0000 0111 : sequence number
0000 0100 : message ID
Body
0000 0000 : sensor ID 0 for general request
0000 0001 : command ID to ask about
Value mappings:
0000 0011 : Size
0000 0010 : type ID 2's comp integer
0000 0000
0000 1011 : size of return name
0111 0011 : s
0110 0101 : e
0110 1110 : n
0111 0011 : s
0110 1001 : i
0111 0100 : t
0110 1001 : i
0111 0110 : v
0110 1001 : i
0111 0100 : t
0111 1001: y
0000 0000
0000 0011 ; SIZE OF return conversion equation
0111 0111 ; x
0010 1111 ; /
0011 0000 ; 0 – conversion equation
0000 0000
0000 0000 : size of value units</td>
<td>The basestation will know what the helper mote's response is supposed to be. If it differs an attack is detected.</td>
</tr>
<tr>
<td><table><tr><td>Attacker</td><td>Target</td></tr><tr><td>Spoofed Mote</td><td>Basestation</td></tr></table>10. Spoof a Command Params Inquiry response packet.</td>
<td>Packet 1:
Header
0000 0000
0000 1000 ; packet size
0000 0000
0000 0111 ; sequence number
0000 0011 ; message ID
Body
0000 0000 : sensor ID 0 for general request
0000 0001 : command ID to ask about
0000 0001 : number of parameters
Param mappings
0000 0010 : Parameter size
0000 0010 : Type ID 2's comp
0000 0000
0000 0111 : Size of param name</td>
<td>The basestation will know what the helper mote's response is supposed to be. If it differs an attack is detected.</td>
</tr>
</table>

	0111 0011 : s 0110 0101 : e 0111 0100 : t 0111 0100 : t 0110 1001 : i 0110 1110 : n 0110 0111 : g – param name 0000 0000 0000 0101 : size of restriction set 0011 0000 : 0 0010 0000 : (space) 0010 1101 : - 0010 0000 : (space) 0011 0101 : 5 0000 0000 : size of parameter units	

7.2.4 Spoofing Basestation to Target Motes

A third type of adversary is if the attacker was a spoofed basestation. The basestation, being the master in this BAN, has a lot of power and capabilities. Figure 22 presents a better understanding of this type of attack.



Attacker Spoofs Base Station message

Figure 22: Spoofed Basestation Attacks

Table 6 shows different attacks that can be accomplished by spoofing the basestation.

Table 6: Spoofed Basestation Attacks

Spoof Basestation (Type A)		
Description of Attack Vectors	Application Packet/Modifications to BT Frame	Detection Mechanism
Attacker: Spoofed Basestation Target: Mote 1. Learning mote commands and then spoofing basestation packets to motes for them to execute commands.	0000 0000 0000 0101 ; packet size 0000 0000 0000 0111 ; sequence number 1111 1111 ; message ID	The helper motes should never receive a command.
Attacker: Spoofed Basestation Target: Mote 2. Sending too many packets can make it so a mote is too busy processing incoming packets to deal with legitimate communications with basestation. DOS attacks such as this are known to drain battery life significantly. [22]	It doesn't really matter what is in the packets themselves. It may be a good idea to spoof source address in the Bluetooth frame, but that's not necessary for the attack.	After an initialization with the BAN PnP Protocol, the motes should only receive coordination messages for the message system. These messages will be encrypted so they will be easily distinguishable from spoofed packets.
Attacker: Spoofed Basestation Target: Motes 3. Spoof packets with incrementing sequence numbers in header so basestation and mote's sequence numbers become out of sync.	Packet 1: 0000 0000 0000 0101 ; packet size 0000 0000 0000 0111 ; sequence number 0000 0000 ; message ID Packet 2: 0000 0000 0000 0101 ; packet size 0000 0000 0000 1000 ; sequence number 0000 0000 ; message ID Packet 3: 0000 0000 0000 0101 ; packet size 0000 0000 0000 1001 ; sequence number 0000 0000 ; message ID	In the current implementation the motes ignore this field. Documentation suggested this field was important and used. Therefore this needs to be detected (by keeping track of incoming sequence numbers).
Attacker: Spoofed Basestation Target: Motes 4. Spoof a Sensor Inquiry.	Packet 1: Header 0000 0000 0000 1000 ; packet size 0000 0000 0000 0111 ; sequence number 0000 0001 ; message ID	After an initialization with the BAN PnP Protocol, the motes should only receive message system coordination messages. As this is not a message system message, the attacker would be detected.
Attacker: Spoofed Basestation Target: Motes	Packet 1: Header 0000 0000 0000 1000 ; packet size 0000 0000	After an initialization with the BAN PnP Protocol, the motes should only receive message

5. Spoof a Command Inquiry.	0000 0111 ; sequence number 0000 0010 ; message ID 0000 0000 : sensor ID 0 for general request	system coordination messages. As this is not a message system message, the attacker would be detected.
Attacker: Spoofed Basestation / Target: Motes 6. Spoof a Command Params Inquiry.	Packet 1: Header 0000 0000 0000 1000 ; packet size 0000 0000 0000 0111 ; sequence number 0000 0011 ; message ID 0000 0000 : sensor ID 0 for general request 0000 0001 : command ID to ask about	After an initialization with the BAN PnP Protocol, the motes should only receive message system coordination messages. As this is not a message system message, the attacker would be detected.
Attacker: Spoofed Basestation / Target: Motes 7. Spoof a Data Inquiry.	Packet 1: Header 0000 0000 0000 1000 ; packet size 0000 0000 0000 0111 ; sequence number 0000 0101 ; message ID 0000 0000 : sensor ID 0 for general request	After an initialization with the BAN PnP Protocol, the motes should only receive message system coordination messages. As this is not a message system message, the attacker would be detected.
Attacker: Spoofed Basestation / Target: Motes 8. Spoof a Command Returns Inquiry.	Packet 1: Header 0000 0000 0000 1000 : packet size 0000 0000 0000 0111 : sequence number 0000 0100 : message ID 0000 0000 : sensor ID 0 for general request 0000 0001 : command ID to ask about	After an initialization with the BAN PnP Protocol, the motes should only receive message system coordination messages. As this is not a message system message, the attacker would be detected.

With this honeypot model, all the information needed to be able to implement the honeypot is documented.

8 Wearable Honeypot Testing and Results

To make the Wearable Honeypot worthwhile it had to meet some design goals. The first of which is to be able to attract an attacker which was shown in the "Attacker Attraction Message System" section. Next it has to be specific to the BAN and Bluetooth protocol which was shown in the "Honeypot Detection Mechanisms" section. The two other design goals were to be more efficient than standard encryption and to be able to effectively detect attackers.

8.1 Honeypot Lifetime Tests

To test that the honeypot system is more efficient than standard encryption a control was needed. AES block cipher is the most secure standard cipher available for TinyOS. This was easily used on Android as well. Because simply encoding with the block cipher isn't very secure, the encryption was done in *cipher block chaining* mode.

8.1.1 Methodology

As part of implementing the message system a high security channel was encrypted with AES-128 bit in cipher block chaining mode. For a comparision of the efficiency of the honeypot, there was also a battery test of real accelerometer data collected from the ADC which was encrypted before sending at BAN's default rate of 32 Hz. The Honeypot message system was then run at the following data rates: 40 Hz, 100 Hz, 70 Hz and finally 50 Hz. The procedure for each test was as follows:

1. Charge Mote
2. Flash mote with firmware version for the configurations above.
3. Pair motes with basestation
4. Run basestation application and add mote to BAN
5. Basestation records time when connected to BAN
6. Mote streams data until dead
7. Basestation records time when mote stops streaming
8. Basestation calculated time elapsed and outputs to screen

Each test was on the 2 motes with the largest form factor and then the results of both tests were averaged.

8.1.2 Results

The results of the tests as outlined in the previous section are summarized in the following graph in figure 23.

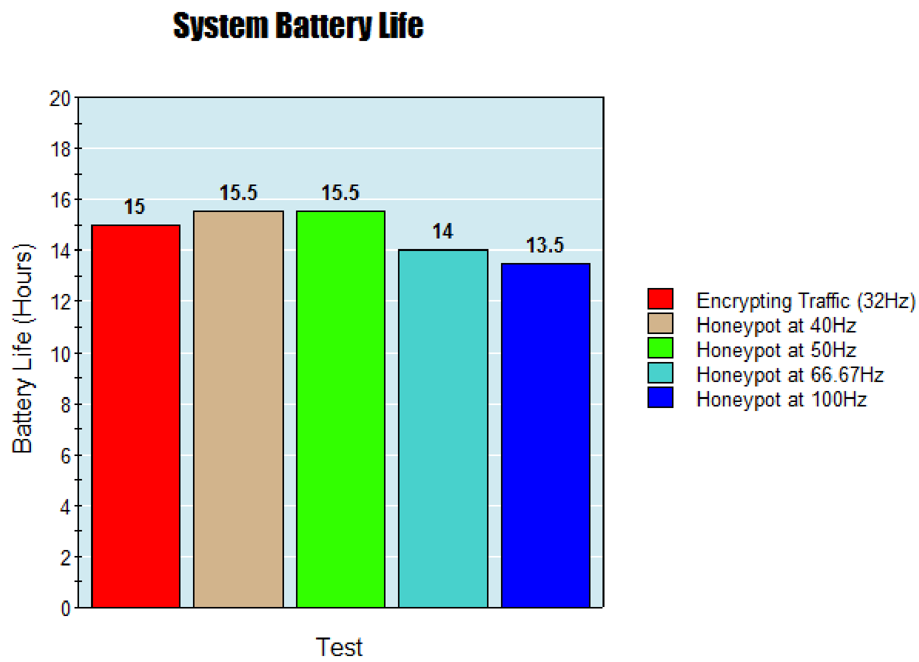


Figure 23: Battery Testing Results

The graph clearly shows that the honeypot can be run almost twice as fast as the BAN normally is before the honeypot becomes less battery efficient than the motes. One could look a this and say that the honeypot only saves a half hour over encryption. However the encryption test was run at 32Hz where the honeypot tests were run at much faster data rates. Additonally, the encryption would be running on the same motes that are needed as sensors, taking away from their operating life. The honeypot runs independently of those devices and doesn't drain their battery. In this way even at nearly double the default data rate the honeypot will provide security to the system longer than encryption without impacting the battery performance of the necessary sensor motes.

8.2 Attack Detection

The final design goal to be met is to effectively detect attacks. For this the original plan was to mount Bluetooth attacks. For this purpose an Ubertooth One Bluetooth testing device was procured [24]. The Ubertooth One can channel hop to all Bluetooth channels and the version of firmware released in summer 2014 is documented to be able to inject packets [24]. This device was set up and packet capture with kismet was initiated. This worked in the sense that many many Bluetooth packets were sniffed. However the packets that were sniffed were just other packets in the vicinity from relatively nearby Bluetooth devices. This sort of promiscuous packet capture mode was not able to help with mounting attacks because while it may be able to hop around and sniff on every Bluetooth channel, it can't sniff on all channels in the same instant.

The Ubertooth One in addition to interfacing with Kismet has its own firmware commands. One command is *ubertooth-follow* which allows the user to specify the *LAP* (Lower Address Portion) and the *UAP* (Upper Address Portion). For some context, a diagram of a Bluetooth address is shown in Figure 24.

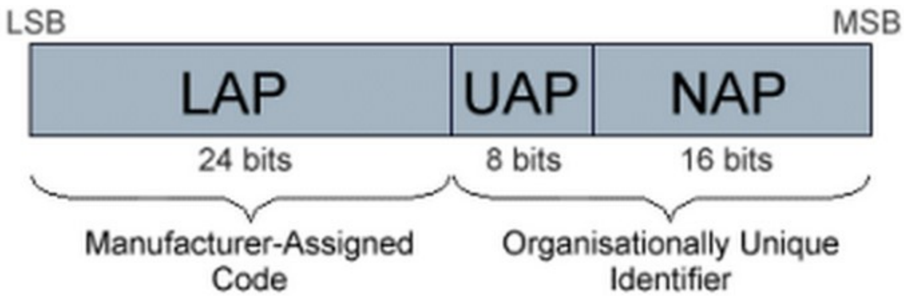


Figure 24: Bluetooth Address Format [22]

This is supposed to lock on the Bluetooth device with the specified address. The software is then supposed to calculate the NAP. One of the Bluetooth addresses in the BAN is (MSB to LSB in HEX): 00:06:66:A0:3A:51. When running the command *ubertooth-follow –uap 66 –lap A0:3A:51* the Ubertooth tries to lock on to 00:00:66:A0:3A:51 which of course doesn't exist. This means it is not calculating the NAP properly. The following command was then attempted *ubertooth-follow –nap 00:06 –uap 66 –lap A0:3A:51.* This command was not accepted (as expected as –nap was not in documentation or help menu). Finally this command was attempted: *ubertooth-follow –uap 06:66 –lap A0:3A:51* and the Ubertooth attempted to lock on to 00:00:0666:A0:3A:51, which is not a valid Bluetooth address. Because of this it was technically infeasible to launch Bluetooth attacks to really detect attackers.

However the detection mechanisms were able to be tested another way. When it comes to Bluetooth disconnection attack detection, this was simulated by blocking the signals from the mote (by wrapping it in tin foil when streaming data) and the basestation realized that the mote was being interfered with. Also, if responses to the BAN PnP requests were modified the honeypot detected the presence of an attacker. Finally, if the wrong honeypot data message was sent the Basestation also detected as an attacker. These results are promising and suggest that the system does effectively detect attacks.

8 Conclusion

The goal of this project was to design and implement a honeypot to add computationally lightweight security to a BAN. The security added by the honeypot acts as an alarm system that detects attacks. The design goals of the system were:

1. To be able to attract attackers to attack it
2. To be specific to the BAN and it's Bluetooth communication
3. To be more efficient than standard encryption
4. To effectively detect attacks

The first of the design goals was met with realistic, pre-determined data stream as explained "Attacker Attraction Message System" part of the "Wearable Honeypot" section. The second design goal was met with a detailed list of all attacks that work on the BAN protocol and Bluetooth as shown in the "Honeypot Detection Mechanisms" part of the "Wearable Honeypot" section. The honeypot also met its third design goal of being more efficient than standard encryption with AES in *cipher block chaining* mode as shown in the "Honeypot Lifetime Tests" part of the testing and results section. The final design goal of effectively detecting attacks wasn't able to be directly tested by mounting a Bluetooth attack, however tests suggest that the detection mechanisms do work as explained in the "Attack Detection" part of the testing and results section.

The honeypot detects attacks in two ways. It can detect when the BAN PnP protocol requests are tampered with as well as data stream (sensor data) tampering. It can do this because the honeypot knows the responses to the requests and it knows exactly what sensor data values should be being transmitted. As you can see the *Wearable Honeypot* has met its design goals.

9 Future Works

The project focused on making a honeypot. There are improvements that could be done to the design topology of the honeypot as well as to the message system. Future projects could expand the features and detection mechanisms of the honeypot, as well as provide attacker response. The *Wearable Honeypot* merely raises the alarm.

9.1 Honeypot Topology Changes

The honeypot could be expanded to 3 or more motes (or virtualized/spoofed motes). The *Wearable Honeypot* uses 2 motes and sends many packets; if more motes are used, then each mote can be less active and still have the same effect (2 motes transmitting 100% of the time is the same amount of traffic as 3 motes 67% of the time). This could lighten the load of each honeypot mote. Relatedly, each member of the BAN could be part of the honeypot meaning the transmission load of the honeypot could be spread as much as possible. However, if that is done, watch out for attracting the attacker towards a mote that would have very bad consequences for the user if it's targeted.

9.2 Message System Extensions

The message system as it is set to transmit in a constant fashion. This rate is changeable, but currently there isn't a good scheduling mechanism for changing the rate dynamically. That is the mote can take any rate, but the base station doesn't have intelligence in setting it. An improvement would involve a more complicated schedule of transmissions where transmission is happening less often, but should still be able to provide the same level of security.

9.3 Responding To Attacks

In terms of security and securing the BAN, responding to attacks would be most important. It wasn't necessary for the purposes of this honeypot to individually recognize different attacks. It merely raises the alarm when an attack is detected. When responding to attacks it may be useful to set up different flags or some data structure to individually recognize all attacks. After detecting precisely which attack was launched, an appropriate response can be determined. This can be through a threat level mapping, where each attack it mapped to a security level. When the security level changes, there is different behavior in the BAN (stronger/weaker encryption, going radio silent temporarily, more extensive logging, etc.) Responses could also be individual to the attack, or some combination of both.

In short, there are multiple different avenues to continue this project on. These are mainly modifying/improving what the honeypot and responding to attacks. In particular, responding to attacks would improve security. Whichever road future projects take, this honeypot should be a usable foundation.

10 References

[1] R. Danas, D. Lally, N. Miller, J. Synnot. ”Enhancing Plug and Play Capabilities in Body Area Network Protocols." *Worcester Polytechnic Institute*. Web. 10 March 2014. <http://www.wpi.edu/Pubs/E-project/Available/E-project-031014-160634/>.

[2] Ho, Chiung Ching, and Choo-Yee Ting. "A Conceptual Framework for Smart Mobile Honeypots." *Academia.edu*. Multimedia University: Faculty of Computing and Informatics, n.d. Web. 8 Oct. 2014. <https://www.academia.edu/3156352/A_Conceptual_Framework_for_Smart_Mobile_Honeypots>.

[3] Juul, Niels Christian. "The Security Hole in WAP: An Analysis of the Network and Business Rationales Underlying a Failure." *International Journal of Electronic Commerce* 7.4 (2003): 73-92. *JSTOR*. Web. 14 Oct. 2014. <http://www.jstor.org/stable/10.2307/27751078?ref=no-x-route:c100b1dc45f58b201f79498b09ea5c00>.

[4] Liebergeld, Steffen, Matthias Lange, and Ravishankar Borgaonkar. "Next Generation Factory Layouts: Research Challenges and Recent Progress." *Interfaces* 32.6 (2002): 58-76. *Cellpot: A Concept for Next Generation Cellular Network Honeypots*. Web. 7 Oct. 2014. <http://www.internetsociety.org/sites/default/files/02_1-paper_0.pdf>.

[5] Mulliner, Collin, Steffen Liebergeld, and Matthias Lange. "Poster: HoneyDroid - Creating a Smartphone Honeypot." *Poster: HoneyDroid - Creating a Smartphone Honeypot* (2011): n. pag. *Poster: HoneyDroid - Creating a Smartphone Honeypot*. IEEE. Web. 8 Oct. 2014. <http://www.ieee-security.org/TC/SP2011/posters/HoneyDroid__Creating_a_Smart_Phone_Honeypot.pdf>.

[6] Song, Yubo, Xiaoyun Zhu, Yelin Hong,, Haoyue Zhang, and Hangbo Tan. "A Mobile Communication Honeypot Observing System." *IEEE Xplore*. Southeast University: Information Science and Technology Department, 2012. Web. 7 Oct. 2014. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6407408>.

[7] Wählisc, Matthias, André Vorbach, Christian Keil, Jochen Schönfelder, Thomas C. Schmidt, and Jochen H. Schiller. "Deutsche Telekom AG Thomas C. Schmidt HAW Hamburg

Christian Keil." *Design, Implementation and Operation of a Mobile Honeypot* 1 (2013): 1-6. *Arxiv*. Web. 7 Oct. 2014. <http://arxiv.org/pdf/1301.7257v1.pdf>.

[8] Wählisch, Matthias, Sebastian Trapp, Christian Keil, Jochen Schönfelder, Thomas C. Schmidt, and Jochen Schiller. "First Insights from a Mobile Honeypot." *ACM SIGCOMM Computer Communication Review* 42.4 (2012): 305. *Google Scholar*. Web. 9 Oct. 2014. <http://page.mi.fu-berlin.de/waehl/papers/wtkss-fimh-12.pdf>.

[9] Roose, Kevin "Here's How Apple Will Convince You to Buy a Smartwatch" *NYMAG.* 10 Sept. 2014. Web. < http://nymag.com/daily/intelligencer/2014/09/how-apple-will-convince-you-to-buy-a-smartwatch.html>

[10] "CodeBlue: Wireless Sensors for Medical Care | Harvard Sensor Networks Lab," [Online]. Available: http://fiji.eecs.harvard.edu/CodeBlue.

[11] Shimmer, Shimmer User Manual.

[12] Shimmer, "Wearable Sensor Technology | Shimmer | Wearable Wireless Sensing Technology and Solutions.," [Online]. Available: <http://www.shimmersensing.com/>

[13] Riden, Jamie, and Christian Seifert. "A Guide to Different Kinds of Honeypots." *Endpoint, Cloud, Mobile & Virtual Security Solutions*. Symantec, 2 Nov. 2010. Web. 15 Oct. 2014. < http://www.symantec.com/connect/articles/guide-different-kinds-honeypots>

[14] K.K. Venkatasubramanian, C. Shue. "Adaptive Information Security in Body Sensor-Actuator Networks." In Proc. of 2014 Usenix Summit on Health Information Technologies Aug 2014.

[15] Peter, Eric, and Todd Schiller. "A Practical Guide to Honeypots." *A Practical Guide to Honeypots*. N.p., 15 Apr. 2008. Web. 1 Oct. 2014. <http://www.cs.wustl.edu/~jain/cse571-09/ftp/honey.pdf >

[16] Even, Loras R. "Intrusion Detection FAQ: What Is a Honeypot?" *SANS:*. N.p., 12 July 2000. Web. 17 Sept. 2014. < http://www.sans.org/security-resources/idfaq/honeypot3.php>

[17] Pietro, Roberto Di and Mancini, Luigi. "Security and privacy issues of handheld and wearable wireless devices." *ACM.* Web. 8 Oct 2014. <http://cacm.acm.org/magazines/2003/9/6721-security-and-privacy-issues-of-handheld-and-wearable-wireless-devices/fulltext>.

[18] Jovanov, Dr. Emil. "Wireless Body Area Networks for Health Monitoring." *Dr. Aleksandar*

Milenković. University of Alabama, n.d. Web. 16 Oct. 2014. <http://www.ece.tufts.edu/ee/194HHW/papers/milenkovic_compcomm06.pdf>

[19] R. Danas, D. Lally, N. Miller, J. Synott, C. Shue, H. Ghasemzadeh, K. K. Venkatasubramanian, "Designing User-specific Plug-n-Play into Body Area Networks", *In Proc. of 4th ACM MobiHoc Workshop on Pervasive Wireless Healthcare* (MobileHealth), Aug 2014. http://delivery.acm.org/10.1145/2640000/2633655/p13-danas.pdf?ip=130.215.17.178&id=2633655&acc=ACTIVE%20SERVICE&key=7777116298C9657D%2E71E5F5E88B9A3E17%2E4D4702B0C3E38B35%2E4D4702B0C3E38B35&CFID=585865375&CFTOKEN=38887012&__acm__=1413581198_df4c72dcfd2ddc8730f3e91f652d0416

[20] "THE PURPOSE OF CRYPTOGRAPHY." An Overview of Cryptography. November 16, 2014. Accessed November 24, 2014. http://www.garykessler.net/library/crypto.html.

[21] Kuperman, Benjamin. "Prevention and Detection of Stack Buffer Overflow Attacks." Prevention and Detection of Stack Buffer Overflow Attacks. August 12, 2005. Accessed November 20, 2014. https://engineering.purdue.edu/~vijay/papers/2005/bo-cacm.pdf.

[22] Chai, Elaina, Ben Deardorf, and Cathy Wu. "Hacking Bluetooth." Hacking Bluetooth. December 9, 2012. Accessed December 1, 2014. http://css.csail.mit.edu/6.858/2012/projects/echai-bendorff-cathywu.pdf.

[23] Gratton, Dean. "The Generic Object Exchange Profile." In *BLUETOOTH PROFILES: The Definition Guide*. Upper Saddle River, New Jersy: Bernard M. Goodwin, 2003. https://books.google.com/books?id=08eByqhzJ3wC&pg=PA356&lpg=PA356&dq=bluetooth+disconnect+request+packet&source=bl&ots=vXcYNZBERf&sig=e3Bq_o6XspjPM-hym4s-mQkWGD0&hl=en&sa=X&ei=626MVLj_ArSOsQT494C4CA&ved=0CCQQ6AEwAQ#v=onepage&q&f=false

[24] "Ubertooth One." Project Ubertooth. Accessed January 5, 2014. http://ubertooth.sourceforge.net/hardware/one/.

[25] Dearman, Chris. "Git." Android / Platform/external/bluetooth/bluedroid /. July 2, 2013.

Accessed December 7, 2014.
https://android.googlesource.com/platform/external/bluetooth/bluedroid/
/f2fc54d237a24dc4db307cb56a513a8720809f95.

[26] Yen, Li-Hsing. "Introduction to Bluetooth." Introduction to Bluetooth. Accessed December 15, 2014.

[27] Bluetooth SIG. "Bluetooth Development Portal." Bluetooth Development Portal. January 1, 2014. Accessed December 15, 2014. https://developer.bluetooth.org/Pages/default.aspx.

[28] "Get Started with AWS." Amazon Web Service. January 1, 2014. Accessed December 18, 2014. http://aws.amazon.com/.

[29] Lustrek, Mitja, Bostjan Kaluza, Rok Piltaver, Jana Krivec, and Vedrana Vidulin. "Localization Data for Posture Reconstruction." UCI Machine Learning Repository. October 1, 2010. Accessed February 20, 2016. https://archive.ics.uci.edu/ml/machine-learningdatabases/00196/ConfLongDemo_JSI.txt.

[30] Saito, Mutsuo Saito, and Makoto Matsumoto Matsumoto. "Tiny Mersenne Twister (TinyMT): A Small-sized Variant of Mersenne Twister." TinyMT. January 1, 2011. Accessed February 15, 2015. http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/TINYMT/index.html.

[31] Denis, Tom St Denis. "Rc4.c." Google Git. November 16, 2006. Accessed February 14, \ 2015. https://android.googlesource.com/platform/external/dropbear/ /donut-release/libtomcrypt/src/prngs/rc4.c.

[32] Eppstein, David Eppstein. "Mersenne Twister." Pseudocode. February 12, 2015. Accessed February 15, 2015. http://en.wikipedia.org/wiki/Mersenne_twister.

Appendix

A.1 Bluetooth Background Info

A.1.1 Device ID

Every Bluetooth device has a device ID or Bluetooth Address which is used to identify it. The address is a 48-bit number just like an Ethernet MAC [26]. Unlike with an Ethernet MAC, a Bluetooth address is used at all levels, not just the physical one. In a piconet all devices transmit using the masters Bluetooth address. The Bluetooth address has 3 parts: 2 bytes for the Non-sigificant Address Portion (NAP), 1 byte for Upper Address Portion (UAP), and 3 bytes for the Lower Addresss Portion (LAP). They are in that order MSB to LSB. While in discoverable mode or in use, Bluetooth addresses are always discoverable [22].

A.1.2 Pairing

Before two devices can exchange data, they must be paired. Master devices initiate pairing by the process shown in the Figure 25.

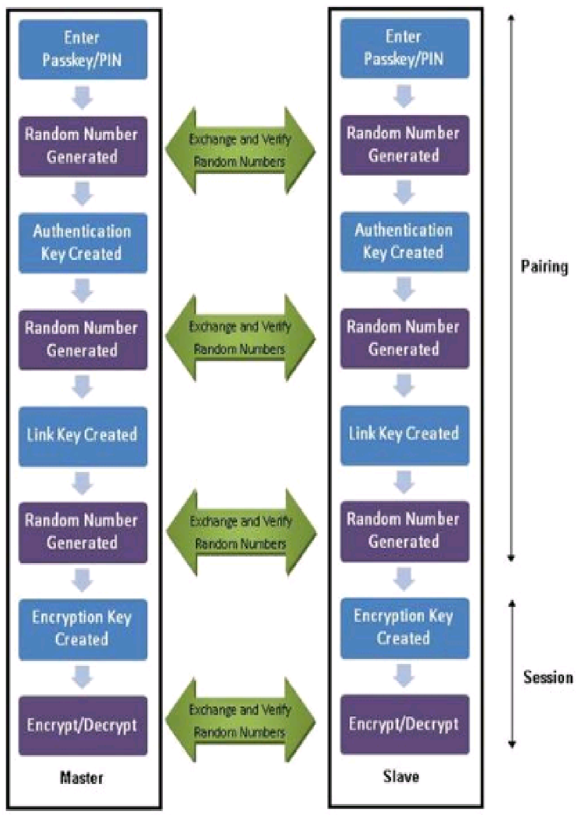


Figure 25: Bluetooth Pairing Process

The pairing process usually usual starts at with a user entering a PIN into a UI. The PIN is the basis for confirming the identity of the devices. After sending a PIN a number of keys are generated for Bluetooth security. The PIN is not transmitted over the wireless channel, instead it is used to generate a random number that becomes the basis for the authentication key. The initialization key is used to agree upon a link key, which depends on the type of communication desired. The link key is then used to generate the encryption key used for built in Bluetooth security [22]. The devices are officially paired at this point.

A.1.3 Frequency Hopping

When a Bluetooth piconet is established from a master, there 14 channels specified for communication. The master transmits on the seven even channels and the slaves transmit using the seven odd channels. Devices hop channels every 625 microseconds [27]. When communicating, the master and all the slaves user the master's device ID to determine hopping patter and the master's clock synchronizes the hopping pattern in th epiconet. When a packet is being transmitted, hopping halts. After one 625 microsecond cycle if the packet is transmitted, then the frequency hops continue. Otherwise after 3 cycles if the packet is done channel hopping resumes. The maximum transmission time of a packet is only allowed to be 5 of these cycles, at which time frequency hopping must resume; frequency hopping may only resume after 1, 3, or 5 cyles [27].

A.1.4 Bluetooth Stack

The Bluetooth stack has 3 layers: Application, Middleware and Transport Layer. The application layer contains all applications on a Bluetooth ready device. The Transport Layer deals with both the physical and logical communication between two devices. The middle layer provides Bluetooth services and decides how the application layer packets get handed to the transport layer. This stack is depicted in Figure 26.

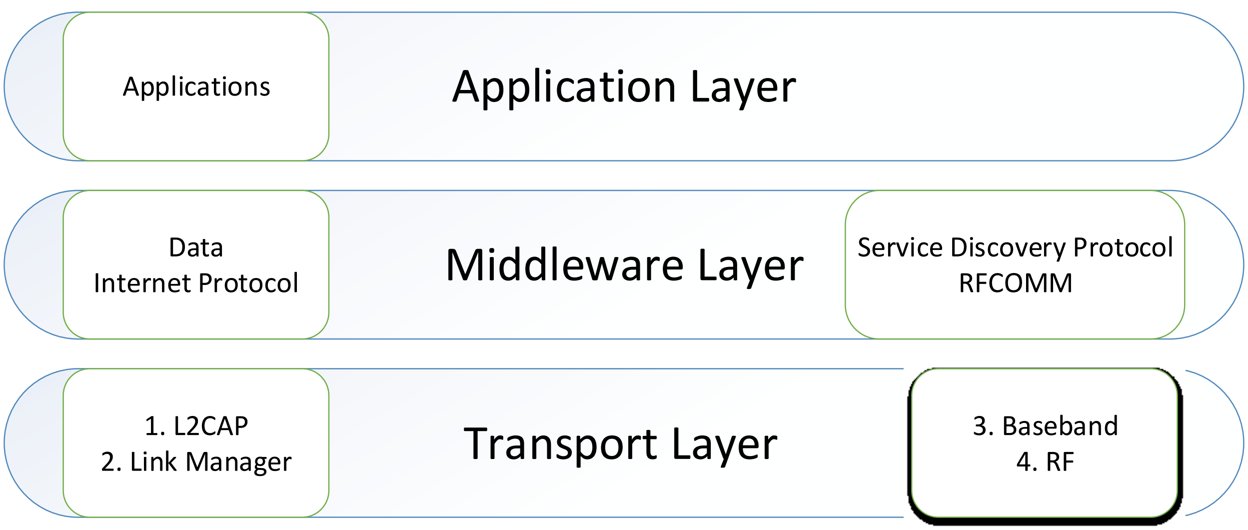


Figure 26: Bluetooth Protocol Stack

The Application layer and the Middleware layer are a set of programs that co-mingle on those levels of the stack. For the transport layer however, L2CAP (Logical Link Control and Adaptation) interfaces with the Link Manger which deals with the logical connection between devices which sits on top of the Baseband which sits on RF both of which deal with the physical communication. RF refers to the physical radio signals and the Baseband controls the time domain multiplexing of the signal. The middleware layer provides services such as TCP/IP, Data Transmission, Service Discover Protocol, and RFCOMM

A.1.5 Bluetooth Security

Bluetooth security is meant to provide authentication, confidentiality, and authorization. That is verify the identify of communicating devices, maintaining communication privacy, and resource control by permissions. It uses a PIN for authorization (this is how authentication key is generated in pairing), verifying the link key is meant to verify the identity of the communication partner, and the encryption key is meant to keep confidentiality.

A.1.5.1 Device ID

Bluetooth addresses are supposed to be globaly unique like Ethernet MAC addresses. This is particularly important because Bluetooth uses a broadcast medium so the communication target must be uniquely identified. An attacker could compile a list of Bluetooth addresses, and use software to change their address and iterate through the list listening for packets. When it finds an address with packets, sniffing and packet injection become possible [22]. This kind of spoofing of an attacker's own address can be very useful because using standard Bluetooth devices, promiscuous sniffing is not possible. This is because most Bluetooth firmware automatically filters out packets not meant for a particular machine [22]. Even in non-dicoverable mode Bluetooth devices will still receive packets addresses to them.

A.1.5.2 Pairing

There are security issues with the paring process. The simplest of which is if this initial pairing communication is eavesdropped, then an attacker would have the authentication key, the link key, and then encryption key rendering Bluetooth level security useless. Also, PINs, which are used for authorization and to initiate pairing, are often left to their default values, making the security measure often useless.

A.1.5.3 Frequency Hopping & Other

Frequency hopping provides some barrier to sniffing, but there are ways around it by modifying firmware or with dedicated devices. Frequency jamming attack has been documented to cause devices to re-initiate pairing allowing an attacker to have the legitimate devices pair with fake ones that provide the foundation for man in the middle attacks [22]. Even with frequency hopping piconets are susceptible to DOS attacks from inquiry scanning. Inquiry scanning is how Bluetooth devices discover each other. Messages of this type are sent over many frequencies.

A.2 Development Issues

A.2.1 Issues with Banmqp implementation

1. Problem: Basestation crashing when motes added to BAN because inside mote constructor isStreaming = wasStreaming = false.
    1. Fix: When variables initialized separately bug went away
1. Problem: Defined in his main menu where strings to hold sensor information that weren't defined in his other xml files.
    1. Fix: Defined the strings
2. Problem: In his main menu there was a closing tag as well that wasn't open on that same row where those strings would have been displayed
    1. Fix: Added the needed ending tag
3. Problem: Only had 8 sensor strings defined in the XML which means if you try to add beyond the fourth row you hit some sort of max in the code
    1. Fix: increasing max to what's actually defined
4. Problem: NULL Items grabbed in a for each loop (if there is a null element in a data structure, the for each construct shouldn't process that)
    1. Fix: Check for NULL in every for each loop
    2. Note: There were also many null pointer exceptions pertaining to trying to process elements in a data structure. Where the log came up null pointer checks were placed.

A.2.2 Development Issues

1. Never edit the source code from the motes and the basestation simulataneously in the same instance of Eclipse. This will cause Eclipse to throw tons and tons of errors.
2. On the motes whenever any configuration file is changed in any way or added to the project, the run configuration must be redone. It will have all the same settings as before, but a new one must be generated or the motes will not flash.

A.2.3 Development Best Practices

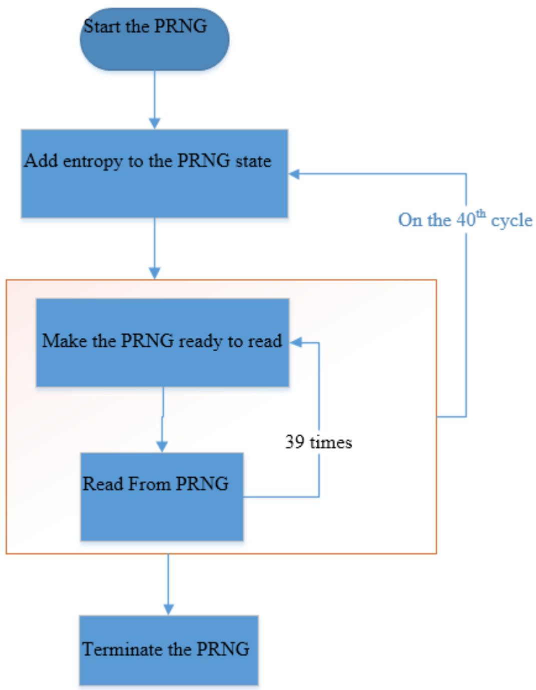
1. Git commit as often as possible.
2. The only simple method to get feedback from motes is the LED, use it.
3. To get feedback from the basestation application, usb connected android phones transmit system activity over the USB, visible in Eclipse w/ ADT.

4. The Shimmer manual explains how to program nesC for TinyOS better than the official documentation.

A.3 PRNGs

A.3.1 RC4

A.3.1.1 Flowchart

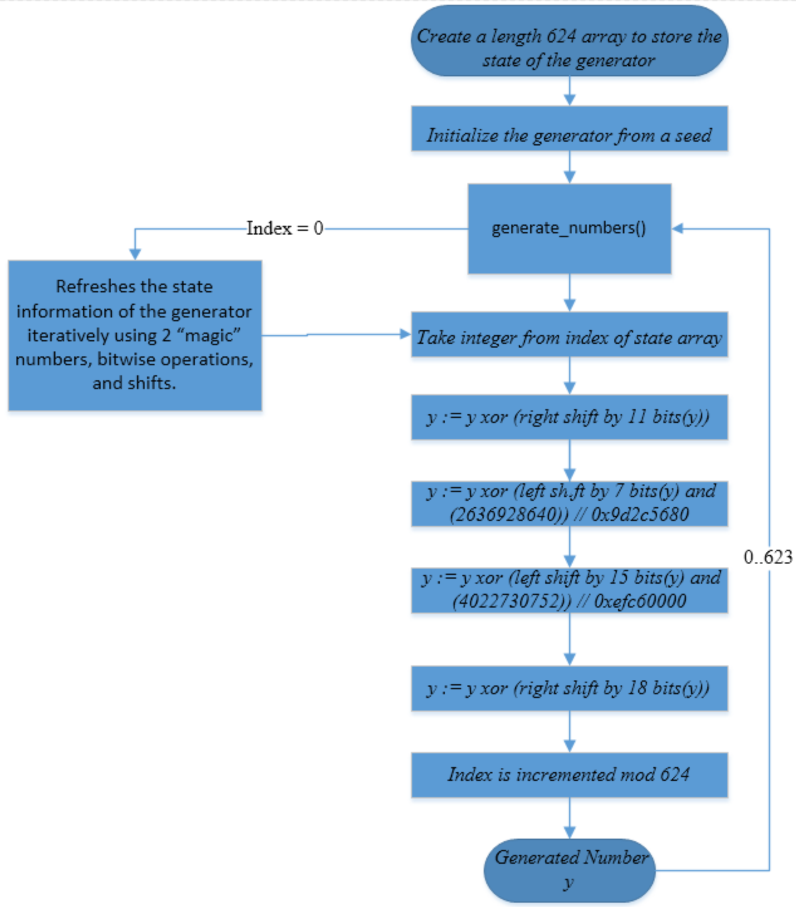


A.3.1.2 Source

[31]

A.3.2 Mersenne Twister

A.3.2.1 Flowchart



A.3.2.2 Source

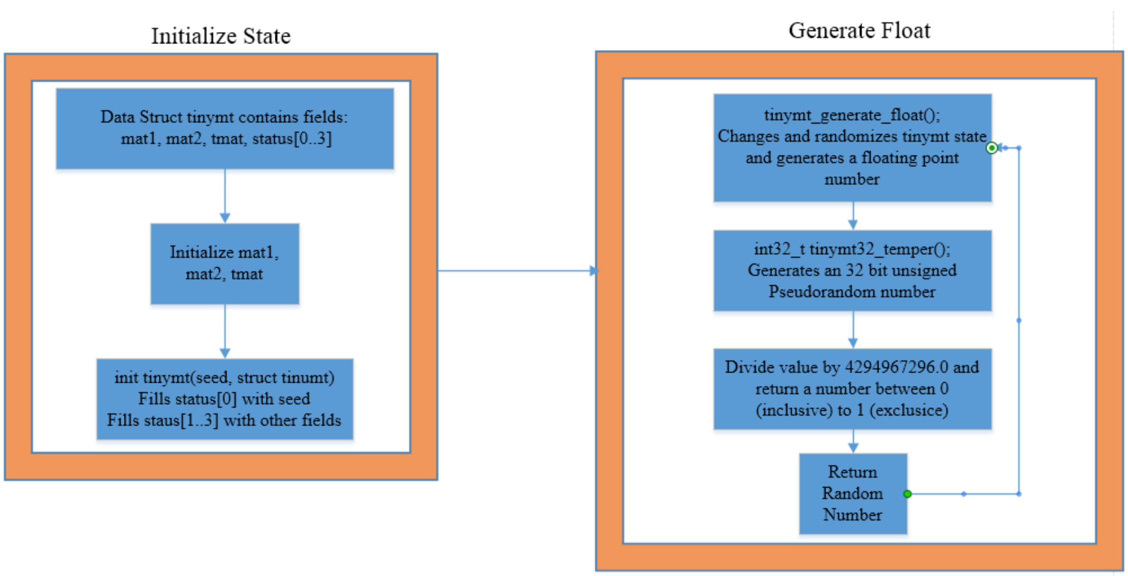
```
// Create a length 624 array to store the state of the generator
 int[0..623] MT
 int index = 0

 // Initialize the generator from a seed
 function initialize_generator(int seed) {
    index := 0
    MT[0] := seed
    for i from 1 to 623 { // loop over each element
       MT[i] := lowest 32 bits of(1812433253 * (MT[i-1] xor (right shift by 30 bits(MT[i-1]))) + i) // 0x6c078965
    }
 }

 // Extract a tempered pseudorandom number based on the index-th value,
 // calling generate_numbers() every 624 numbers
 function extract_number() {
    if index == 0 {
       generate_numbers()
    }
```

```
    int y := MT[index]
    y := y xor (right shift by 11 bits(y))
    y := y xor (left shift by 7 bits(y) and (2636928640)) // 0x9d2c5680
    y := y xor (left shift by 15 bits(y) and (4022730752)) // 0xefc60000
    y := y xor (right shift by 18 bits(y))

    index := (index + 1) mod 624
    return y
}

// Generate an array of 624 untempered numbers
function generate_numbers() {
    for i from 0 to 623 {
        int y := (MT[i] and 0x80000000)                 // bit 31 (32nd bit) of MT[i]
                    + (MT[(i+1) mod 624] and 0x7fffffff)   // bits 0-30 (first 31 bits) of MT[...]
        MT[i] := MT[(i + 397) mod 624] xor (right shift by 1 bit(y))
        if (y mod 2) != 0 { // y is odd
            MT[i] := MT[i] xor (2567483615) // 0x9908b0df
        }
    }
}
```

[32]

A.3.3 TinyMT

A.3.3.1 Flowchart



A.3.3.2 Source

```
#ifndef TINYMT32_H
#define TINYMT32_H
/**
 * @file tinymt32.h
 *
 * @brief Tiny Mersenne Twister only 127 bit internal state
```

```
 *
 * @author Mutsuo Saito (Hiroshima University)
 * @author Makoto Matsumoto (University of Tokyo)
 *
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 */

#include <stdint.h>
#include <inttypes.h>

#define TINYMT32_MEXP 127
#define TINYMT32_SH0 1
#define TINYMT32_SH1 10
#define TINYMT32_SH8 8
#define TINYMT32_MASK UINT32_C(0x7fffffff)
#define TINYMT32_MUL (1.0f / 4294967296.0f)

#if defined(__cplusplus)
extern "C" {
#endif

/**
 * tinymt32 internal state vector and parameters
 */
struct TINYMT32_T {
    uint32_t status[4];
    uint32_t mat1;
    uint32_t mat2;
    uint32_t tmat;
};

typedef struct TINYMT32_T tinymt32_t;

void tinymt32_init(tinymt32_t * random, uint32_t seed);
void tinymt32_init_by_array(tinymt32_t * random, uint32_t init_key[],
                            int key_length);

#if defined(__GNUC__)
/**
 * This function always returns 127
 * @param random not used
 * @return always 127
 */
inline static int tinymt32_get_mexp(
    tinymt32_t * random  __attribute__((unused))) {
    return TINYMT32_MEXP;
}
#else
inline static int tinymt32_get_mexp(tinymt32_t * random) {
    return TINYMT32_MEXP;
}
```

```
#endif

/**
 * This function changes internal state of tinymt32.
 * Users should not call this function directly.
 * @param random tinymt internal status
 */
inline static void tinymt32_next_state(tinymt32_t * random) {
    uint32_t x;
    uint32_t y;

    y = random->status[3];
    x = (random->status[0] & TINYMT32_MASK)
            ^ random->status[1]
            ^ random->status[2];
    x ^= (x << TINYMT32_SH0);
    y ^= (y >> TINYMT32_SH0) ^ x;
    random->status[0] = random->status[1];
    random->status[1] = random->status[2];
    random->status[2] = x ^ (y << TINYMT32_SH1);
    random->status[3] = y;
    random->status[1] ^= -((int32_t)(y & 1)) & random->mat1;
    random->status[2] ^= -((int32_t)(y & 1)) & random->mat2;
}

/**
 * This function outputs 32-bit unsigned integer from internal state.
 * Users should not call this function directly.
 * @param random tinymt internal status
 * @return 32-bit unsigned pseudorandom number
 */
inline static uint32_t tinymt32_temper(tinymt32_t * random) {
    uint32_t t0, t1;
    t0 = random->status[3];
#if defined(LINEARITY_CHECK)
    t1 = random->status[0]
            ^ (random->status[2] >> TINYMT32_SH8);
#else
    t1 = random->status[0]
            + (random->status[2] >> TINYMT32_SH8);
#endif
    t0 ^= t1;
    t0 ^= -((int32_t)(t1 & 1)) & random->tmat;
    return t0;
}

/**
 * This function outputs floating point number from internal state.
 * Users should not call this function directly.
 * @param random tinymt internal status
 * @return floating point number r (1.0 <= r < 2.0)
 */
inline static float tinymt32_temper_conv(tinymt32_t * random) {
    uint32_t t0, t1;
    union {
            uint32_t u;
```

```
            float f;
    } conv;

    t0 = random->status[3];
#if defined(LINEARITY_CHECK)
    t1 = random->status[0]
            ^ (random->status[2] >> TINYMT32_SH8);
#else
    t1 = random->status[0]
            + (random->status[2] >> TINYMT32_SH8);
#endif
    t0 ^= t1;
    conv.u = ((t0 ^ (-((int32_t)(t1 & 1)) & random->tmat)) >> 9)
              | UINT32_C(0x3f800000);
    return conv.f;
}

/**
 * This function outputs floating point number from internal state.
 * Users should not call this function directly.
 * @param random tinymt internal status
 * @return floating point number r (1.0 < r < 2.0)
 */
inline static float tinymt32_temper_conv_open(tinymt32_t * random) {
    uint32_t t0, t1;
    union {
            uint32_t u;
            float f;
    } conv;

    t0 = random->status[3];
#if defined(LINEARITY_CHECK)
    t1 = random->status[0]
            ^ (random->status[2] >> TINYMT32_SH8);
#else
    t1 = random->status[0]
            + (random->status[2] >> TINYMT32_SH8);
#endif
    t0 ^= t1;
    conv.u = ((t0 ^ (-((int32_t)(t1 & 1)) & random->tmat)) >> 9)
              | UINT32_C(0x3f800001);
    return conv.f;
}

/**
 * This function outputs 32-bit unsigned integer from internal state.
 * @param random tinymt internal status
 * @return 32-bit unsigned integer r (0 <= r < 2^32)
 */
inline static uint32_t tinymt32_generate_uint32(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper(random);
}

/**
 * This function outputs floating point number from internal state.
```

```
 * This function is implemented using multiplying by 1 / 2^32.
 * floating point multiplication is faster than using union trick in
 * my Intel CPU.
 * @param random tinymt internal status
 * @return floating point number r (0.0 <= r < 1.0)
 */
inline static float tinymt32_generate_float(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper(random) * TINYMT32_MUL;
}

/**
 * This function outputs floating point number from internal state.
 * This function is implemented using union trick.
 * @param random tinymt internal status
 * @return floating point number r (1.0 <= r < 2.0)
 */
inline static float tinymt32_generate_float12(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper_conv(random);
}

/**
 * This function outputs floating point number from internal state.
 * This function is implemented using union trick.
 * @param random tinymt internal status
 * @return floating point number r (0.0 <= r < 1.0)
 */
inline static float tinymt32_generate_float01(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper_conv(random) - 1.0f;
}

/**
 * This function outputs floating point number from internal state.
 * This function may return 1.0 and never returns 0.0.
 * @param random tinymt internal status
 * @return floating point number r (0.0 < r <= 1.0)
 */
inline static float tinymt32_generate_floatOC(tinymt32_t * random) {
    tinymt32_next_state(random);
    return 1.0f - tinymt32_generate_float(random);
}

/**
 * This function outputs floating point number from internal state.
 * This function returns neither 0.0 nor 1.0.
 * @param random tinymt internal status
 * @return floating point number r (0.0 < r < 1.0)
 */
inline static float tinymt32_generate_floatOO(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper_conv_open(random) - 1.0f;
}

/**
```

```
 * This function outputs double precision floating point number from
 * internal state. The returned value has 32-bit precision.
 * In other words, this function makes one double precision floating point
 * number from one 32-bit unsigned integer.
 * @param random tinymt internal status
 * @return floating point number r (0.0 < r <= 1.0)
 */
inline static double tinymt32_generate_32double(tinymt32_t * random) {
    tinymt32_next_state(random);
    return tinymt32_temper(random) * (1.0 / 4294967296.0);
}

#if defined(__cplusplus)
}
#endif
#endif

/**
 * @file tinymt32.c
 *
 * @brief Tiny Mersenne Twister only 127 bit internal state
 *
 * @author Mutsuo Saito (Hiroshima University)
 * @author Makoto Matsumoto (The University of Tokyo)
 *
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 */
#include "tinymt32.h"
#define MIN_LOOP 8
#define PRE_LOOP 8

/**
 * This function represents a function used in the initialization
 * by init_by_array
 * @param x 32-bit integer
 * @return 32-bit integer
 */
static uint32_t ini_func1(uint32_t x) {
    return (x ^ (x >> 27)) * UINT32_C(1664525);
}

/**
 * This function represents a function used in the initialization
 * by init_by_array
 * @param x 32-bit integer
 * @return 32-bit integer
 */
static uint32_t ini_func2(uint32_t x) {
    return (x ^ (x >> 27)) * UINT32_C(1566083941);
}
```

```
/**
 * This function certificate the period of 2^127-1.
 * @param random tinymt state vector.
 */
static void period_certification(tinymt32_t * random) {
    if ((random->status[0] & TINYMT32_MASK) == 0 &&
            random->status[1] == 0 &&
            random->status[2] == 0 &&
            random->status[3] == 0) {
            random->status[0] = 'T';
            random->status[1] = 'I';
            random->status[2] = 'N';
            random->status[3] = 'Y';
    }
}

/**
 * This function initializes the internal state array with a 32-bit
 * unsigned integer seed.
 * @param random tinymt state vector.
 * @param seed a 32-bit unsigned integer used as a seed.
 */
void tinymt32_init(tinymt32_t * random, uint32_t seed) {
    random->status[0] = seed;
    random->status[1] = random->mat1;
    random->status[2] = random->mat2;
    random->status[3] = random->tmat;
    int i;
    for (i = 1; i < MIN_LOOP; i++) {
            random->status[i & 3] ^= i + UINT32_C(1812433253)
                * (random->status[(i - 1) & 3]
                  ^ (random->status[(i - 1) & 3] >> 30));
    }
    period_certification(random);
    for (i = 0; i < PRE_LOOP; i++) {
            tinymt32_next_state(random);
    }
}

/**
 * This function initializes the internal state array,
 * with an array of 32-bit unsigned integers used as seeds
 * @param random tinymt state vector.
 * @param init_key the array of 32-bit integers, used as a seed.
 * @param key_length the length of init_key.
 */
void tinymt32_init_by_array(tinymt32_t * random, uint32_t init_key[],
                                    int key_length) {
    const int lag = 1;
    const int mid = 1;
    const int size = 4;
    int i, j;
    int count;
    uint32_t r;
    uint32_t * st = &random->status[0];
```

```
    st[0] = 0;
    st[1] = random->mat1;
    st[2] = random->mat2;
    st[3] = random->tmat;
    if (key_length + 1 > MIN_LOOP) {
            count = key_length + 1;
    } else {
            count = MIN_LOOP;
    }
    r = ini_func1(st[0] ^ st[mid % size]
                        ^ st[(size - 1) % size]);
    st[mid % size] += r;
    r += key_length;
    st[(mid + lag) % size] += r;
    st[0] = r;
    count--;
    for (i = 1, j = 0; (j < count) && (j < key_length); j++) {
            r = ini_func1(st[i % size]
                          ^ st[(i + mid) % size]
                          ^ st[(i + size - 1) % size]);
            st[(i + mid) % size] += r;
            r += init_key[j] + i;
            st[(i + mid + lag) % size] += r;
            st[i % size] = r;
            i = (i + 1) % size;
    }
    for (; j < count; j++) {
            r = ini_func1(st[i % size]
                          ^ st[(i + mid) % size]
                          ^ st[(i + size - 1) % size]);
            st[(i + mid) % size] += r;
            r += i;
            st[(i + mid + lag) % size] += r;
            st[i % size] = r;
            i = (i + 1) % size;
    }
    for (j = 0; j < size; j++) {
            r = ini_func2(st[i % size]
                          + st[(i + mid) % size]
                          + st[(i + size - 1) % size]);
            st[(i + mid) % size] ^= r;
            r -= i;
            st[(i + mid + lag) % size] ^= r;
            st[i % size] = r;
            i = (i + 1) % size;
    }
    period_certification(random);
    for (i = 0; i < PRE_LOOP; i++) {
            tinymt32_next_state(random);
    }
}


/* This one was changed for our purposes
 * main.c
```

```
 */
/**
 * @file check32.c
 *
 * @brief Simple check program for tinymt32
 *
 * @author Mutsuo Saito (Hiroshima University)
 * @author Makoto Matsumoto (The University of Tokyo)
 *
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 * LICENSE.txt
 */
#include <stdio.h>
#include <stdint.h>
#include <inttypes.h>
#include <stdlib.h>
#include "tinymt32.h"

int main(int argc, char * argv[]) {
   tinymt32_t tinymt;
   tinymt.mat1 = (uint32_t) 0xEFEFEFEF;
   tinymt.mat2 = (uint32_t) 0x12345678;
   tinymt.tmat = (uint32_t) 0xABCDEF12;
   uint32_t seed = 0x1321FBCA;
   tinymt32_init(&tinymt, seed);
   tinymt32_generate_floatOC(&tinymt); // float between 0 and 1;
   return 0;
}
```

[30]