An Enhanced Body Area Network to Wirelessly Monitor Biometric Information

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Master of Science

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ABSTRACT
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An Enhanced Body Area Network to Wirelessly Monitor Biometric Information

Director of Thesis: Chris G. Bartone

Body Area Networks are beneficial in many applications including fitness tracking and remote healthcare monitoring. This thesis discusses system enhancements to the award-winning Ohio University Body Area Network system which senses heart rate, integrates an inertial measurement unit, and measures ambient temperature. An upgraded ARM-based Nordic microprocessor was implemented to collect and process biometric sensor data and utilize low-energy Bluetooth (BLE) to transmit data via a Bluetooth antenna. Data is received on an updated Android application running on a handheld Nexus 5 Smartphone. Power received measurements were performed to compare the Baseline and Enhanced systems using several Bluetooth antenna solutions including an e-textile spiral antenna, a traditional inset-fed patch antenna, and a printed monopole antenna.
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for their respective university research and development programs, as well as IEEE AP-S for hosting the student design contest in which we took part. Finally, I would like to thank the Ohio University Russ College of Engineering and Technology for their support in many ways. Without these organizations, the Ohio Body Area Network would not exist.

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<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Page</strong></td>
</tr>
<tr>
<td>Abstract ...............................................................................................................................</td>
</tr>
<tr>
<td>Acknowledgments .............................................................................................................</td>
</tr>
<tr>
<td>List of Tables ..................................................................................................................</td>
</tr>
<tr>
<td>List of Figures ...............................................................................................................</td>
</tr>
<tr>
<td>Definitions of Symbols and Abbreviations .......................................................................</td>
</tr>
<tr>
<td>Chapter 1: Introduction ..................................................................................................</td>
</tr>
<tr>
<td>Chapter 2: Background ...................................................................................................</td>
</tr>
<tr>
<td>Motivation ....................................................................................................................</td>
</tr>
<tr>
<td>Medical Costs ..............................................................................................................</td>
</tr>
<tr>
<td>Remote Healthcare Monitoring ...................................................................................</td>
</tr>
<tr>
<td>Body Area Networks ....................................................................................................</td>
</tr>
<tr>
<td>Design Limitations and Requirements ........................................................................</td>
</tr>
<tr>
<td>Components of Body Area Networks ..........................................................................</td>
</tr>
<tr>
<td>Data Collection and Wireless Communications ........................................................</td>
</tr>
<tr>
<td>2015 IEEE AP-S Student Design Contest .....................................................................</td>
</tr>
<tr>
<td>Overview of Requirements .........................................................................................</td>
</tr>
<tr>
<td>Baseline Ohio BAN System ..........................................................................................</td>
</tr>
<tr>
<td>Sensor Subsystem .......................................................................................................</td>
</tr>
<tr>
<td>Microcontroller and Interface Subsystem ..................................................................</td>
</tr>
<tr>
<td>Bluetooth Antenna Design .........................................................................................</td>
</tr>
<tr>
<td>Android Application Development ............................................................................</td>
</tr>
<tr>
<td>Chapter 3: Project Scope .............................................................................................</td>
</tr>
<tr>
<td>Chapter 4: Methodology and Design .............................................................................</td>
</tr>
<tr>
<td>Enhanced Ohio BAN System Description ....................................................................</td>
</tr>
<tr>
<td>Sensor Subsystem .......................................................................................................</td>
</tr>
<tr>
<td>Microcontroller and Transceiver Subsystem ............................................................</td>
</tr>
<tr>
<td>Bluetooth Antenna Considerations ............................................................................</td>
</tr>
<tr>
<td>Android Application Development ............................................................................</td>
</tr>
<tr>
<td>Chapter 5: Results and Discussion .............................................................................</td>
</tr>
<tr>
<td>System Level Testing ..................................................................................................</td>
</tr>
</tbody>
</table>
Power Received Measurements and Comparisons ............................................... 57
Power Budget Analysis ......................................................................................... 61
Chapter 6: Conclusion....................................................................................................... 64
Chapter 7: Recommendations for Future Work.......................................................... 66
References ......................................................................................................................... 67
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1 - Baseline Ohio BAN system RSSi Power Received Measurements by Smartphone</td>
<td>58</td>
</tr>
<tr>
<td>Table 2 - Enhanced Ohio BAN system RSSi Power Received Measurements by Smartphone</td>
<td>60</td>
</tr>
<tr>
<td>Table 3 - Baseline Ohio BAN system Current Consumption Analysis</td>
<td>62</td>
</tr>
<tr>
<td>Table 4 - Enhanced Ohio BAN system Current Consumption Analysis</td>
<td>63</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline Ohio BAN system block diagram</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>Heart Rate Monitor Interface (HRMI) board (51mm x 47mm) with RMCM01 reception antenna</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Required orientation for the Polar heart rate monitor chest strap transmitter and the HRMI board for proper wireless communications</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>ADXL345 digital accelerometer breakout board (20mm x 15mm)</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Baseline Ohio BAN components and wiring diagram</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>Baseline Ohio BAN patch antenna realized gain results from CST with simulated human body layers underneath</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>Fabricated baseline patch antenna (30mm x 30mm) with SMA connector</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>The Ohio BAN patch antenna inside the elastic strap holder (top) and Polar T31 Coded Chest Strap (bottom) for heart rate monitoring</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>Baseline Ohio BAN smartphone application display. (a) Left display: Connecting to a Bluetooth device with an RSSi message display. (b) Right display: Data collection and fall detection displayed</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>HTU21D-F digital temperature sensor (18mm x 16mm)</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>Nordic nRF52 Development Kit Board (100mm x 64mm) with its edge connectors and the nRF52832 SoC (3.2mm x 3.0mm) highlighted</td>
<td>38</td>
</tr>
<tr>
<td>12</td>
<td>The BLE advertising process whereas a peripheral device advertises and a central device responds with a scan response request in order to connect [31]</td>
<td>40</td>
</tr>
<tr>
<td>13</td>
<td>GATT structure for the Enhanced Ohio BAN system</td>
<td>41</td>
</tr>
<tr>
<td>14</td>
<td>Enhanced Ohio BAN wiring diagram</td>
<td>48</td>
</tr>
<tr>
<td>15</td>
<td>The Enhanced Ohio BAN biometric sensors mounted atop the nRF52 development kit with SWF RF connector for external Bluetooth antenna solutions</td>
<td>49</td>
</tr>
<tr>
<td>16</td>
<td>The Enhanced Ohio BAN system inside a clear plastic enclosure with power switch and SMA female connector for external Bluetooth antenna options</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>nRF52 DK printed monopole antenna and SWF RF connector</td>
<td>51</td>
</tr>
<tr>
<td>18</td>
<td>Edge-fed e-textile spiral antenna worn on the body with supporting foam board underneath</td>
<td>53</td>
</tr>
<tr>
<td>19</td>
<td>Ohio BAN application screenshot listing available Bluetooth devices and their RSSi value</td>
<td>54</td>
</tr>
<tr>
<td>20</td>
<td>Enhanced Ohio BAN application showing biometric data received from the connected Ohio BAN system</td>
<td>56</td>
</tr>
</tbody>
</table>
# DEFINITIONS OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>API</td>
<td>Application Program Interface</td>
</tr>
<tr>
<td>ARM</td>
<td>Advanced Risc Machines</td>
</tr>
<tr>
<td>BAN</td>
<td>Body Area Network</td>
</tr>
<tr>
<td>BLE</td>
<td>Bluetooth Low Energy</td>
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<tr>
<td>CVD</td>
<td>Cardiovascular Disease</td>
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<tr>
<td>dBm</td>
<td>Decibel-milliwatts</td>
</tr>
<tr>
<td>DK</td>
<td>Development Kit</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram Data</td>
</tr>
<tr>
<td>GAP</td>
<td>Generic Access Profile</td>
</tr>
<tr>
<td>GATT</td>
<td>Generic Attribute Profile</td>
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<tr>
<td>HRM</td>
<td>Heart Rate Monitoring</td>
</tr>
<tr>
<td>IDE</td>
<td>Interactive Development Environment</td>
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<tr>
<td>I2C</td>
<td>Inter-Integrated Circuit</td>
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<tr>
<td>ISM</td>
<td>Industrial, Scientific, Medicine</td>
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<tr>
<td>MCU</td>
<td>Microcontroller Unit</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PIFA</td>
<td>Planar Inverted-F Antenna</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SCL</td>
<td>Serial Clock</td>
</tr>
<tr>
<td>SDA</td>
<td>Serial Data</td>
</tr>
<tr>
<td>SDK</td>
<td>Software Development Kit</td>
</tr>
<tr>
<td>SoC</td>
<td>System on Chip</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver/Transmitter</td>
</tr>
<tr>
<td>UUID</td>
<td>Universal Unique Identifier</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

Body area networks are used in many applications pertaining to data collection and analysis for the benefit of the user. These applications include wearable technology, fitness tracking, and remote healthcare monitoring and many products are currently available in the marketplace today. Body area networks must provide relevant data to a user while being safe, durable, lightweight, and non-intrusive. System enhancements were made to the award-winning Ohio University Body Area Network (Ohio BAN) in order to eliminate limitations and upgrade key features. The enhanced Ohio BAN is an all-in-one system that utilizes innovative technology to monitor a user’s biometric data and transmit these data to a smartphone for viewing. The system consists of a heart rate monitoring interface, a triple-axis digital inertial measurement unit for relative position tracking, and a digital thermometer for ambient temperature readings. Data is collected and processed using a new ARM-based microprocessor. Next, the data is transmitted to a smartphone using a low-energy Bluetooth solution using a Bluetooth antenna, and a smartphone application displays biometric information to the user. The system provides limited intrusion to the user and an easy to use user interface. The enhanced system was operationally tested for comparison with the baseline system to show its effectiveness and power efficiency. The enhancements to the system lay the groundwork for future research and development in a variety of potential applications.
CHAPTER 2: BACKGROUND

Motivation

Medical Costs

The cost of providing healthcare in America has steadily increased over the last several decades. In 1950 it was estimated that America’s healthcare expenses made up 5% of the Gross Domestic Product (GDP). Projections indicate that this number will grow to 32%, or $16 trillion by 2030 [1]. In particular, the growth of the elderly population in the United States has provided substantial challenges to the healthcare industry. Among the chronic diseases facing older Americans, cardiovascular disease is the most prevalent and most expensive.

A 2017 study released by the American Heart Association shows that cardiovascular disease (CVD) will run rampant in the next two decades by affecting more people and costing more money than ever before [2]. The study states that by 2035 “the number of Americans with CVD will rise to 131.2 million – 45 percent of the total U.S. population – with costs expected to reach $1.1 trillion” [2]. More Americans will be faced with high blood pressure, coronary heart disease, and stroke than ever before. The study found that older Americans will be at the highest risk. By 2035, Americans over 65 years old will have an 80 percent chance of having CVD [2]. Disease is not the only danger facing our aging population.

As the elderly American population continues to grow, more Americans will risk safety in their own home. The Center for Disease Control states that falls are the number one contributor to injury among older Americans, and 27,000 fall deaths occur each year
In 2014 alone, older Americans experienced 29 million falls causing seven million injuries and costing an estimated $31 billion in annual Medicare costs [3]. In order to reduce disease, injuries, and fatalities, we must seek alternative prevention strategies.

Population-based prevention strategies can provide healthcare intervention advantages with little drawbacks. Epidemiologist Geoffrey Rose introduced the idea of population-based prevention in comparison to individual-based prevention methods [4]. Rose believed that by reducing a risk factor by a small amount for an entire population, more disease can be prevented than by reducing a risk factor by a large amount in the individual patient. “Population-based prevention strategies using cheap and safe interventions can be considerably more effective than strategies that target individuals based on a single elevated risk factor” [5]. In support, Rose theorized in [6] that a population-based strategy to reduce cholesterol and blood pressure would lower the overall rate of heart disease in a region more than an individual strategy which focused on individuals who already had high cholesterol and blood pressure values. This was proven true as Rose’s theory was shown in an epidemiological study on cardiovascular disease in the years following [7]. Rose’s theory can be used to support remote patient monitoring, which could be deployed over a population in order to lower many disease risk factors and ultimately improve well-being and cut rising healthcare costs.

Remote Healthcare Monitoring

Remote healthcare monitoring can be affordable and non-intrusive through the advent of wearable technology. Currently, wearable technology plays a major role in the consumer goods market, and it is starting to play a more prominent role in transforming
healthcare. The wearable technology market as a whole is expected to grow from $20 billion in 2015 to $70 billion in 2025 [8]. Innovative sensors are emerging that provide an accurate health analysis in applications such as diabetes, sleep disorders, obesity, and cardiovascular disease. With the advent of advanced sensing and wearable technologies, all-inclusive systems can be developed to support remote healthcare monitoring.

Body Area Networks

A Body Area Network (BAN) is defined by the Institute of Electrical and Electronics Engineers (IEEE) standard 802.15.6 as a “low power, short range, and extremely reliable wireless communication within the surrounding area of the human body” [9]. The location of a BAN may exist on the surface, inside or in the nearby proximity of the human body. BAN systems are perfectly suitable for remote healthcare monitoring applications, but many requirements exist in order to provide ubiquitous effectiveness.

Design Limitations and Requirements

First and foremost, body area networks must provide comfort to the patient. “Patient comfort, both physically and psychologically, is one of the most essential variables in designing a wearable medical device” [8]. Patient comfort is important because BAN systems may need to be worn for long periods of time. When BANs are made invisible to the user, more accurate results can be provided. To provide the best comfort, BAN systems must be lightweight while being safe and durable.

A BAN system must be applicable to the wellbeing of the individual while providing a user interface that is easy to use for everyone. The system must provide
relevant biomedical data in real time which can be viewed by a user or health official to
diagnosis a user’s health status. To accomplish this, it is important to carefully select the
design components of the BAN system.

Components of Body Area Networks

A BAN consists of one or more biomedical sensors placed on or near the user’s body. The location of BAN sensors vary based on the level of intrusiveness required by the medical sensor. IEEE standard 802.15.6 for Body Area Networks defines the three locations for BAN nodes as implanted inside the human body, on the body surface in direct contact with the skin (or within 2 cm distance), and external of the body (from 2 cm up to 5 m from the body surface) [9]. BAN sensors collect biometric data from the user in real time and typically pass these data to a Microcontroller Unit (MCU) using traditional existing communications protocols.

A BAN uses an MCU located on or near the user. The MCU performs many tasks including receiving biometric data from the sensors, packaging the data, and transmitting it to a device for viewing or storage. Depending on the application, a BAN device may exist as a user’s smartphone or a health official’s device (e.g., remote computer). The BAN device is customized to fit the overall goal of the BAN system.

Data Collection and Wireless Communications

The BAN MCU can be configured using software to control the frequency in which the BAN sensors take measurements on the user. Upon receiving raw sensor data, the MCU may make calculations on the data to correctly format the data. Next, the MCU transmits the data to a device using a traditional or wireless communication protocol. For
a BAN system that is worn completely on the user’s body, a fully wireless system is desired for a minimization of intrusion by sending signals around the human body wirelessly.

IEEE standard 802.15.6 for Body Area Networks states that wireless communications can exist within the existing industrial, scientific, and medical (ISM) bands, as well as other frequency bands approved by regulatory authorities [9].

Developing BAN systems to wirelessly function within the ISM band is beneficial for numerous reasons. For example, the 2.4 GHz spectrum allows for small antennas which can minimize intrusion while maximizing efficiency through a variety of RF designs. Developing in the ISM band is also beneficial for leveraging existing radio designs including Wi-Fi, ZigBee, NFC, and Bluetooth.

2015 IEEE AP-S Student Design Contest

In 2015, a fully operating BAN system was created by Ohio University as part of the 2015 IEEE Antennas and Propagation Society (AP-S) Student Design Contest [10]. The overall goal of the contest was to “design and build an antenna that is optimized for on-body placement in a BAN application of your choice, such as fall detection or monitoring of vital signs” [11]. The created Baseline Ohio BAN system provided the basis for the Enhanced Ohio BAN system focus for this thesis.

Overview of Requirements

The Student Design Contest consisted of many specifications for the design of a BAN system which shaped the Baseline Ohio BAN system [11]. First, the BAN system was to consist of a data-collecting sensor connected to a Bluetooth transceiver. The
transceiver is connected to the antenna to transfer the data to a custom-built Android smartphone application. The sensor and transceiver were to be purchased off-the-shelf. Next, the Bluetooth transceiver was to comply with the Bluetooth standard and be able to operate at Class 3 power rating \((\leq 1 \text{ mW})\) and the BAN system should be battery-powered [11].

The Bluetooth antenna was required to be safe and durable, easily reproducible and lightweight [11]. The antenna structure (excluding sensor, transceiver and battery) was to be no larger than 30 mm in length, 30 mm in width, and 5 mm in height. The custom Android application was required to display BAN system specific data as well as the power received from the system, for comparison of link performance in terms of received power in decibel-milliwatts (dBm).

Finally, the BAN system was to be tested in test scenarios which simulate its operation. “Test scenarios should include the antenna system being skin-mounted on the upper front part of the torso and the smartphone positioned at each of these three locations: 1 m in front of the torso, in the front pocket, and in the back pocket of wearer’s pants. There should be no other objects within 2 m of the system, except for the smartphone operator” [11]. The contest allowed existing licensed university software to be used, but the total production cost of the entire system was not to exceed US$1,500.

Baseline Ohio BAN System

Figure 1 shows the Baseline Ohio BAN system that measures and transmits a user’s biometric data using a Bluetooth antenna and displays the data in a custom-built application on an Android smartphone [12]. The heart rate monitor (HRM) sensor is worn
as a chest strap and communicates to the HRM interface (HRMI) board via a low-frequency data link. Additionally, temperature and positional data is collected using a temperature sensor and an inertial measurement unit, respectively. The sensor data is processed using a low-cost Arduino Uno microcontroller. The Arduino is interfaced with a Bluetooth Low Energy (BLE) transceiver and an Ohio University custom-designed patch antenna operating in the Bluetooth frequency band. The BAN system transmits sensor data over the 2.4 GHz BLE link to a Google Nexus 5 smartphone which uses an Android operating system. The smartphone displays a user’s heart rate, ambient temperature, and fall detection data in an Ohio University custom-made application. The system was demonstrated to properly function with the Bluetooth antenna mounted on the user’s torso, and with the smartphone in three test locations: held 1 m in front of the torso, in the user’s front pocket, and in the user’s back pocket [12].
The Ohio BAN system measures human biometric data using advanced sensors which are small in size for on-body placement. The sensor subsystem includes Heart Rate Monitoring (HRM), and includes provisions for fall detection and ambient temperature readings. Electrocardiogram (ECG) data is collected directly on the wearer’s body by using a chest strap sensor and transmitter [12].

The Polar T31 Coded Chest Strap was selected for its accuracy and reliability in heart rate monitoring applications [12]. Polar chest strap transmitters are widely used in applications such as fitness tracking and other wearable technologies currently on the
market. Its low frequency wireless link allows for the Polar HRMI board to be separated from the Polar chest strap transmitter. Using a magnetic loop antenna operating at 5.5 kHz, Polar chest strap transmitters can wirelessly send ECG data from the body to the HRMI board. The 5.5 KHz HRM data link provides less attenuation around and through the human body than higher microwave frequencies. The HRMI board receives an ECG signal using a RMCM-01 Polar OEM receiver and converts it to usable heart rate data values using an advanced algorithm, even in the midst of noisy environments. Figure 2 shows the HRMI breakout board with the RMCM01 reception antenna.

![HRMI breakout board with RMCM01](image)

Figure 2 - Heart Rate Monitor Interface (HRMI) board (51mm x 47mm) with RMCM01 reception antenna

The HRMI boasts support of many communication interfaces including USB, serial, and I²C. Its functionality offers two algorithm modes for data processing including raw mode and average mode, and its data history buffers can store up to 32 past heart rate
measurement values at any given time. The HRMI evaluation board requires 5-V operation, making it ideal for low-power body area networks used in remote healthcare monitoring [12] [13].

In order for the HRMI to be operational for the Ohio BAN system, it must be properly configured on the body. According to its datasheet, the maximum distance between the chest strap transmitter and the HRMI should not exceed 80 cm [13]. On the HRMI, the RMCM01 magnetic loop receiver antenna coils detect the magnetic field generated by the chest strap transmitter coils. “The receiver should be in parallel with the magnetic flow generated by the transmitter for maximum energy transfer” [13]. This proper orientation is illustrated in Figure 3.

![Figure 3 - Required orientation for the Polar heart rate monitor chest strap transmitter and the HRMI board for proper wireless communications](image)

Fall detection was implemented using the low-cost ADXL345 digital Micro-Electro-Mechanical Systems (MEMS) Inertial Measurement Unit (IMU) [12] [14].
Included in the ADXL345 breakout board is a three-axis accelerometer. The ADXL345 IMU is a very small and lightweight sensor, making it ideal for wearable applications. It is powered by a 3.3-V source and monitors acceleration along x, y, and z axes relative to its breakout board location.

The ADXL345 measures the static acceleration of gravity as well dynamic acceleration resulting from sudden motion, such as free fall. It offers high resolution (13-bit) measurements and has support for SPI or I2C digital interfaces, and it supports both standard (100 kHz) and fast (400 kHz) data transfer modes.

The ADXL345 provides state-of-the-art motion detection functions for movement tracking which could be utilized in a host of remote monitoring applications. Custom event monitoring can be set in software to track specific events based on various applications. The ADXL345 could track events such as inactivity, impact detection, or free fall sensing. This can be accomplished using one of two included interrupt output pins on the breakout board. Additionally, “an integrated, patent pending 32-level first in, first out (FIFO) buffer can be used to store data to minimize host processor intervention” [14]. The ADXL345 offers low power modes based on activity levels as well as an overall extremely low power dissipation. It is ideal for body area networks because of its size, precision, and functionalities.

This IMU was specifically programmed to rapidly take two samples and difference them to detect a change in acceleration, which allows prediction when a user may have experienced a fall or similar event. “Since the time-differenced acceleration data are taken over a relatively short period of time (i.e., one second), the drift of the
MEMS sensors is of little concern. If the fall threshold is exceeded in any one of the three directions monitored, then an alert is sent to the microcontroller on the I²C-bus” [12]. The fall detection threshold is set using software in the Arduino Uno microcontroller, and it can be altered to fit any BAN application using the versatile ADXL345 IMU. Figure 4 below shows the ADXL345 accelerometer breakout board. (Note: The ADXL345 accelerometer does not include gyroscopes).

![Figure 4 - ADXL345 digital accelerometer breakout board (20mm x 15mm)](image)

For ambient temperature measuring, the DS18B20 digital thermometer was implemented [12] [15]. The DS18B20 boasts a 12-bit accuracy which translates to ±0.5 °C. The DS18B20 requires a 5-V power source, and is interfaced for communications using the Serial Peripheral Interface (SPI). “The digital thermometer here was used to measure ambient temperature; however, an additional sensor could be added to measure actual body temperature” [12]. All of the sensors were directly connected to the Arduino microcontroller digital input pins for data processing.
Microcontroller and Interface Subsystem

The Arduino Uno R3 microcontroller was selected because of its ease of use [12]. The Arduino provided 16 Kbytes of flash memory and 2 Kbytes of RAM with its ATmega16U2 microcontroller chip. The Arduino receives biometric data from the sensors and packages the data for Bluetooth transmission. “BLE was selected for the BAN-to-phone link, rather than more traditional Bluetooth protocols (e.g., Bluetooth 3.0), due to the requirement for battery operation, low power, and periodic data updates (i.e., non-streaming), for this body-wearable application” [12]. To make the system BLE functional, a Nordic BLE transceiver was implemented as part of the nRF8001 BLE Development Kit offered by Nordic Semiconductor. “The BLE transceiver board [nRF2741 with a subminiature version A (SMA) radio-frequency (RF) connector] was interfaced to the Arduino Uno microcontroller via an interface board” [12]. The radio output level is software adjustable from -18 to 0 dBm, and it was specifically set to 0 dBm to ensure compliance with the Class 3 power rating requirement set forth by the design contest specifications. The nRF8001 DK provides a BLE sensitivity of -87 dBm [16]. Figure 5 shows the Baseline Ohio BAN wiring diagram the interconnections between the major components.
Bluetooth Antenna Design

The Bluetooth antenna was designed based on the requirement of having an operating frequency in the 2.4 GHz industrial, scientific, and medical (ISM) band which spans 2.40-2.48 GHz. Several antenna types were considered including a bent dipole array, a Planar Inverted-F Antenna (PIFA), and a patch antenna [12]. “The initial design considered a two-element linear endfire dipole array printed on a dielectric substrate, placed parallel to the chest, such that the main beam would be pointed more in the downward direction toward the smartphone held in the hand, front pocket, or back pocket” [12]. However, the implementation of the endfire dipole array was too prohibitive given the antenna size constraints. The PIFA design provided a smaller size,
but had a 3 dB reduction in gain (i.e., half the gain of a comparable patch antenna). This
degradation ruled out the PIFA since it needed to provide a robust Bluetooth connection
with the smartphone in a wearable application. The final design consideration was an
inset-fed patch antenna with a ground plane, which was selected for the Baseline Ohio
BAN system. The patch antenna design was beneficial because the ground plane
provided excellent isolation from the lossy human body and it enabled respectable gain in
the forward direction off the wearer’s torso [12]. One disadvantage of the patch antenna
design was the rigidity, which is addressed in the Enhanced Ohio BAN System.

The final inset-fed patch antenna was modeled and built on Roger’s Thermoset
Microwave Material TMM6 which has a relative permittivity of 6.3 and a loss tangent of
0.0023 [17]. The patch antenna was modeled using Computational Electromagnetic
Modeling (CEM) software packages FEKO and CST Microwave Studio [12]. “All full-
wave simulations of the antenna were performed together with a human body layer model
to emulate the torso underneath the antenna structure. Human skin, fat, muscle, and bone
were all simulated under the antenna structure using electrical parameters at 2.4 GHz in
c accordance with IEEE Standard C95.3-2002” [12],[18].

Human body layers added beneath the patch antenna were used in the simulation
to predict the antenna performance mounted on the torso. “First, a human skin layer was
added with a thickness of 0.171 mm. Then, a human fat layer of 1.00 mm was added.
Finally, muscle and bone layers were added at 2.52 and 16.4 mm respectively, which are
all based upon average human biological standards for the human torso” [19]-[21]. Each
human body layer used was found in each respective CEM materials library and were
consistent with IEEE C95.3-2002 [18]. Figure 6 shows the patch antenna realized gain results from CST Microwave Studio atop simulated body layers. The figure below shows the orientation of the antenna directly placed on the user’s torso. The positive x-axis points to the ground below, the positive y-axis points the user’s left hand side, and the positive z-axis points directly perpendicular to the user’s torso. The CEM results indicated excellent gain away from the simulated body layers.

Figure 6 - Baseline Ohio BAN patch antenna realized gain results from CST with simulated human body layers underneath

Once the antenna performance was finalized with the CEMs, the antenna was fabricated using photolithography and a standard photo-etching process in Ohio University laboratories. Figure 7 shows the fabricated patch antenna with SMA connector attached.
After fabrication, the patch antenna was functionally tested using an Agilent 8753 Vector Network Analyzer (VNA) and manually tuned to resonate in the Bluetooth band (i.e., 2.402-2.482 GHz) [22]. Its input impedance was measured as 42.2-j2.9 Ω at 2.45 GHz, which produced a reasonably good match to a 50-Ω connector [12]. The bandwidth was determined to be 62 MHz using a VSWR 2.0:1.0 metric. Despite having a bandwidth lower than the full Bluetooth band (80 MHz), the antenna was not affected due to the functionality of the BLE protocol. “The BLE protocol utilizes both frequency-division multiple access and time-division multiple access techniques, where the Bluetooth band is divided into 40 2-MHz channels that include three advertising at each end of the band, and one in the middle of the band as well as 37 data channels. This robustness in the BLE design helps to overcome any interference and/or signal received in particular channels within the Bluetooth band” [12] [23]. It is made wearable on a user’s torso by using an elastic strap holder, which is worn similarly to the Polar T31 Coded Chest Strap shown in Figure 8.
Figure 8 - The Ohio BAN patch antenna inside the elastic strap holder (top) and Polar T31 Coded Chest Strap (bottom) for heart rate monitoring

The radiation characteristics of the antenna were measured inside Ohio University’s Antenna Anechoic Chamber [24] in accordance with [25]. Far-field radiation pattern measurements were performed at 2.45 GHz for elevation and azimuth cuts. The resulting directivity data for both elevation and azimuth cuts showed excellent coverage away from the body and low gain toward the body, reinforcing the simulated CEM results [12].

**Android Application Development**

The Android application was developed using Android Studio version 0.8.6 and downloaded onto a Google Nexus 5 smartphone running Android OS 4.4.4 KitKat [12]. The application displays biometric data transmitted from the microcontroller via the patch antenna using BLE. The application displays the Received Signal Strength indication (RSSi) message in dBm, the heart rate of the user, fall detection data, and the ambient temperature.
Figure 9 shows two screenshots from the Baseline Ohio BAN smartphone application. Upon starting the application, the user is met with the screen shown in Figure 9a (left display) which allows the user to select a Bluetooth device to establish a connection. This is where the RSSi power level received is displayed. Upon connecting, the user is navigated to the screen shown in Figure 9b, which shows a user’s biometric data. The application displays collected heart rate data, temperature data, and updates them when new data is available. “Upon detecting a fall, the Android device will also provide haptic feedback to the phone” [12]. When the falls-detected display reaches the bottom of the screen, the Impact Detection Log becomes a scrollable log.
The Android application runs BLE communications through a universal asynchronous receiver/transmitter (UART) solution. Upon receiving a BLE message from the transceiver, the application will decipher the message and assign each data value to its corresponding location in the user interface. The application is available for download on the Google Play Store [28].
CHAPTER 3: PROJECT SCOPE

This thesis seeks to enhance the prize-winning Ohio Body Area Network through a series of upgrades to each subsystem. For each of its merits, the previous system was limited for multiple reasons. The sensor subsystem used multiple communication protocols, making the software architecture more complicated than necessary. The Arduino microcontroller provided limited flash memory, low RAM, lack of a Bluetooth function, and the stigma that it is a microcontroller for hobbyist projects. The Bluetooth patch antenna is a rigid solution which can provide discomfort to the wearer. Finally, the Bluetooth link between the system and the smartphone relied on a UART solution instead of taking full advantage of the benefits provided by BLE. Altogether, the physical system was heavy and inconvenient to wear. Each of these issues are addressed in the development of an Enhanced Ohio BAN system.
CHAPTER 4: METHODOLOGY AND DESIGN

Enhanced Ohio BAN System Description

The enhancements to the Ohio BAN system target operational aspects including hardware, firmware, and software upgrades. Largely, the core functionality of the system is held intact, with biomedical sensors relaying information to a microcontroller and then utilizing BLE to communicate biometric data to a user’s smartphone. The system utilizes a novel ARM-based microprocessor with newer firmware and built-in Bluetooth transmission capabilities. Additionally, a new temperature sensor is included which allows for compatibility with the other sensors on the I²C-bus. The overall system has been consolidated to reduce weight, and the Android smartphone application was reworked to enhance BLE transmission operations and usability.

Sensor Subsystem

In order to provide proper health diagnostics for potential remote healthcare monitoring applications, it is necessary to use highly accurate and extremely reliable biomedical sensing technology. Similar to the Baseline Ohio BAN system, the Enhanced System utilizes provisions for tracking relative position data, heart rate monitoring and temperature sensing on a single communications bus.

ADXL345 Accelerometer

Movement tracking is again implemented through the use of the ADXL345 accelerometer breakout board which measures acceleration along three axes. Its small size, high accuracy, and low operating voltage makes it ideal for the Enhanced Ohio BAN System.
**Polar Heart Rate Monitor Interface**

Like the Baseline Ohio BAN System, the Enhanced System uses the Polar HRMI board. This interface allows for compatibility with a Polar Heart Rate Monitor Chest Strap worn on the body [13]. Like the ADXL345, the HRMI board is ideal due to its small size, high accuracy, and low operating voltage.

**I^2C-bus Protocol**

The inclusion of biomedical sensors in a body area network will require a robust digital communications protocol which can handle high data transfer modes provided by the sensors. The Inter-Integrated Circuit (I^2C) bus is the most ideal protocol for connecting sensors to a microcontroller in the enhanced Ohio BAN system. The I^2C-bus is extremely useful due to its popularity and ease of use. “The I^2C-bus is a de facto world standard that is now implemented in over 1000 different ICs manufactured by more than 50 companies” [26]. The I^2C-bus was developed by Philips Semiconductors (now NXP Semiconductors) to integrate unique systems for the benefit of system designers and to create simpler and more efficient circuits [26].

The I^2C-bus boasts many features which greatly help BAN system designers. Only two bus lines are required on the I^2C-bus. These include the Serial Data line (SDA) and a Serial Clock line (SCL) [26]. All sensors added to the I^2C-bus network are connected together in parallel. This streamlines the wiring setup by eliminating excess wiring. This is accomplished because the I^2C-bus utilizes software addressable functionality for peripheral sensor devices. Each peripheral device may be given a unique address to communicate directly with the central processing unit. If two or more devices
concurrently transmit data, the I²C-bus provides collision detection and remediation to prevent data loss. Furthermore, the I²C-bus supports bidirectional and unidirectional data transfers, and uses on-chip filtering to ensure signal integrity [26].

The SDA and SCL lines carry information between the CPU and sensor devices on the I²C-bus. The peripheral sensor devices may act as a transmitter or receiver by sending and receiving data. The number of devices connected on the same I²C-bus is limited only by the capacitance of the bus and the capabilities of the CPU [26].

**HTU21D-F Temperature Sensor**

Another advanced sensor that provides data in a biomedical setting is a digital temperature sensor. The HTU21D-F digital temperature sensor from Adafruit Industries offers a wide measurement range, from -40°C to 125°C and only requires 3-V for operation [27]. It transfers data to a central processor using the I²C digital interface, and it provides its own 8-bit Cyclic Redundancy Check (CRC) code for error detection, making it highly reliable and accurate. Temperature is measured as a 14-bit value, and stored in a register for access by a microcontroller. The use of a high quality temperature sensor such as the HTU21D-F will allow for on-body placement for skin temperature measurements, or ambient temperature readings in the user’s environment. Additionally, it can measure ambient relative humidity, but this function will not be used in the enhanced Ohio BAN system, but could be implemented in other potential device applications.

The HTU21D-F features two different operation modes for communications: Hold Master mode and No Hold Master mode. “No Hold Master mode allows for
processing other I²C communication tasks on a bus while the HTU21D-F sensor is measuring” [27]. Conversely, Hold Master mode completely ties up the I²C-bus while a measurement is taking place. The Enhanced Ohio BAN system operates the HTU21D-F temperature sensing function under No Hold Master mode, allowing the I²C-bus to remain open to all sensors even while a temperature measurement is taking place. Figure 11 shows the HTU21D-F sensor.

![HTU21D-F sensor](image)

Figure 10 - HTU21D-F digital temperature sensor (18mm x 16mm)

Microcontroller and Transceiver Subsystem

Enhancements to the microcontroller and transceiver subsystem were a high priority for the Enhanced Ohio BAN system. In order to reduce the form-factor of the Baseline system, it was desirable to remove the Arduino microcontroller which relied on additional hardware boards for BLE support. The Arduino also limited the software development for the Baseline system because of its reliance on Arduino coding libraries. One of the overall goals of the enhanced system is to provide a foundation in which further development could be continued and to promote miniaturization of the system.
For these reasons it was desirable to select an advanced ARM-based microprocessor that provided innovative features and could be coded in common object-oriented C++. Many microprocessor packages were considered and the selection was made to use the nRF52832 System on Chip from Nordic Semiconductor.

**ARM-based Microprocessor**

The nRF52832 System on Chip (SoC) provides numerous advantages for body area network applications [29]. First, it uses a powerful 32-bit ARM Cortex-M4F processor which is a major upgrade over the ATmega16U2 chip used previously in the Arduino Uno R3 [29]. It boasts an industry-leading 512 Kbytes of flash memory and 64 Kbytes of random access memory (RAM) compared to only 16 Kbytes of flash memory and 2 Kbytes of RAM with the ATmega16U2.

At the time of its creation, the nRF52832 was the world’s smallest Bluetooth low energy SoC, and it provides superior qualities over similar chips on the market [29]. For BLE operations, its embedded Bluetooth transceiver provides a sensitivity of -96 dBm while operating nominally from 1.7 to 3.6-V. The nRF52832 SoC is available to developers in the form of a development kit which is comparable in price to the Arduino Uno.

**Nordic nRF52 Development Kit**

The Nordic nRF52 Development Kit (DK) utilizes the nRF52832 SoC and offers superior amenities for developing body area networks [29]. The nRF52 DK can be powered by a 3-V CR2032 coin cell battery, making it ideal for low-cost and lightweight wearable applications. ARM firmware development on the nRF52 DK is made
conventional due to support for various tool-chains including interactive development environments (IDEs) such as Keil MicroVision, GNU Compiler Collection (GCC), and Segger Embedded Studio [26]. It can be programmed by connecting a USB cable to its on-board micro-USB port from a computer. The nRF52 DK supports multiple digital interfaces such as two-wire interface (a.k.a., I2C), serial peripheral interface (SPI), and general purpose input/output (GPIO), all of which are utilized on its edge connectors, shown in Figure 11.
The nRF52 DK provides advanced functions for BAN research and development. It offers near field communication (NFC) capabilities with built-in NFC antenna connector. Additionally, the nRF52832 SoC Bluetooth transceiver is wired to an on-board monopole Bluetooth antenna printed on its circuit board [29]. The nRF52 DK is an excellent tool for prototyping BAN systems because its components could be arranged into a Printed Circuit Board (PCB) for later downsizing and consolidation of future systems.

**Bluetooth Low Energy**

Due primarily to its energy efficiency and popularity among wireless devices, the Enhanced Ohio BAN system utilizes Bluetooth Low Energy. The BLE Stack in the Ohio BAN system is contained within the S132 SoftDevice from Nordic Semiconductor. A SoftDevice is an Application Program Interface (API) software package which performs wireless protocol tasks for Nordic-based microprocessor devices. The SoftDevice must be programmed separately onto the nRF52 DK. “The S132 SoftDevice integrates a BLE Controller and Host, and provides a full and flexible API for building Bluetooth Smart nRF52 System on Chip solutions” [30]. The S132 SoftDevice is Bluetooth 4.2 compliant, and supports complementary software development for BLE applications using the nRF52 Software Development Kit (SDK) example projects.

The BLE stack contained in the SoftDevice features many layers. First, the Generic Access Profile (GAP) controls the connections and advertising in the Bluetooth protocol [31]. GAP makes it so peripheral Bluetooth devices can be found and connected to central devices. Advertising refers to a data payload which is broadcasted from a
peripheral device for a limited amount of time. If a central device such as a mobile phone detects advertising data, it can send a scan response request if it is interested in connecting. The peripheral device may send additional scan response data to the central device to initiate a connection. Figure 12 shows the advertising process initiated by the peripheral device [31].

![Figure 12 - The BLE advertising process whereas a peripheral device advertises and a central device responds with a scan response request in order to connect [31]](image)

When a Bluetooth connection is established, the advertising process is stopped. Next, the peripheral device will share its Generic Attribute (GATT) profile which contains services and characteristics holding transmitted data. BLE peripheral devices may only be connected to one central device at a time, meaning GATT can only be exclusively shared to one device at any given time. GATT is made up of layers called profiles, services, and characteristics.

A GATT profile refers to the collection of services belonging to a BLE peripheral device. The profile manages the transfer of data using its services and characteristics which hold the information. Services are used to split data into specific categories which can be cycled through by the central device [31].
Each service of a GATT profile has its own Universally Unique Identifier (UUID) which is a 16-bit value that differentiates it from other services. Services contain one or more characteristics, which contain the transmitted data values [31].

Characteristics also have their own 16-bit UUID value. Characteristics may be given read and write privileges in order for a central device to receive and send data between itself and a peripheral device. The benefit of using GATT is that it uses small packet sizes which reduces power consumption, truly making it a low-energy Bluetooth solution [31]. The GATT structure for the Ohio BAN system is shown below in Figure 13.

![GATT structure for the Enhanced Ohio BAN system](image)

Figure 13 - GATT structure for the Enhanced Ohio BAN system
**Software Architecture**

The nRF52832 microprocessor accomplishes two major tasks for the Enhanced Ohio BAN system: operate its Bluetooth functions, and communicate with sensors over I\(^2\)C using its two-wire interface. Upon powering up the Enhanced Ohio BAN system, several Bluetooth functions are initiated. First, the SoftDevice and BLE event interrupt is initiated, thus starting the BLE stack events. Subsequently, GAP is initialized, setting up the necessary parameters of the device including the device name, appearance, and the preferred connection parameters. Next, GATT is initialized, setting up the Ohio BAN system profile. Then, the advertising function, the services, and the connection parameters module are all initialized respectively. Finally, advertising begins and the nRF52832 BLE initiation is complete.

For I\(^2\)C communications, the nRF52832 will act as a master device, meaning it will initiate commands and generate clock signals to allow data transmission between itself and the sensor subsystem. The sensor devices connected on the I\(^2\)C-bus will act as slave devices, meaning they are addressed by the master device. The nRF52832 SoC uses 7-bit I\(^2\)C addressing meaning 128 devices can be connected simultaneously on the I\(^2\)C-bus [29]. The nRF52832 firmware was specifically developed for the Enhanced Ohio BAN system in order to target each sensor on the I\(^2\)C-bus to receive biometric data in return. In order to start using the I\(^2\)C-bus protocol, the two-wire interface (TWI) is initialized after device advertising begins. The nRF52832 microprocessor uses a timer event handler function which communicates with each sensor and eventually packages data for BLE transmission.
The nRF52832 microprocessor issues commands to the HRMI by reading and writing to the device’s I²C address using a custom-made driver function. Commands are a 1- or 2-byte (8- or 16-bit) I²C write sequence [13]. Responses from the HRMI consist of one or more bytes containing numeric values representing heart rate data. In order to send a command to get heart rate data, the host controller must issue a write sequence of “<0x47><0xN>”, where “N” is the number of heart rate samples to request. The heart rate history buffer on the HRMI keeps up to 31 user 8-bit heart rate values. For the Ohio BAN system, the nRF52 will need to issue a write sequence requesting the most recent heart rate value. In order to do so, the nRF52832 microprocessor will write the sequence “<0x47><0x01>” to the device’s I²C address. In order to receive data, the host controller must issue a read command for the correct amount of data bytes to be received. The HRMI datasheet states that “the HRMI stretches the clock on the SCL line during the read while it fetches data bytes internally to satisfy the read” [13]. A pre-allocated buffer is used to store received data on the nRF52832 microprocessor. Ultimately, this data is packaged and sent to a user’s smartphone using BLE.

Similar to the HRMI, the nRF52832 microprocessor reads accelerometer data by sending commands to the ADXL345 device’s I²C address. The ADXL345 device’s on-board registers contain device information and relevant data [14]. In order to read data from the ADXL345, the device must first be put into measurement mode by writing a non-zero value to the POWER_CTL register. Data can be accessed by requesting a read from registers 0x32, 0x34, and 0x36, which respectively contain x, y, and z position data. The nRF52832 microprocessor reads the response from the ADXL345 by placing the
relative position data into a received data buffer. The relative position data is accessed from the buffer and assigned to its respective measurement value of \( x \), \( y \), or \( z \).

Furthermore, the output data rate and bandwidth can be controlled by the nRF52832 microprocessor. By writing the value “0x0A” to the BW_RATE register, the ADXL345 has an output data rate of 100 Hz and a Bandwidth of 50 Hz [14].

The HTU21D-F temperature sensor is utilized using the same software methods as the HRMI and ADXL345. In order to receive temperature data, the nRF52832 microprocessor must issue a command of “0xF3” to the device’s I2C address [27]. Upon receiving a raw 14-bit temperature value, the nRF52832 microprocessor converts it to Celsius as shown in equation (1) below, where \( S_{\text{Temp}} \) denotes the 14-bit temperature signal output [27].

\[
\text{Temperature} \ (^{\circ}C) = -46.85 + 175.72 \times \frac{S_{\text{Temp}}}{2^{16}}
\]  

(1)

As mentioned previously, the nRF52832 microprocessor for the Enhanced Ohio BAN system uses a timer event handler to execute readings from the sensors and package the data for BLE transmission. The timer event handler is a software-defined loop which executes every second (1000 ms). First, it collects biometric data by making function calls to the HRMI, ADXL345, and HTU21D-F devices. After the data collection process ends, all the data is converted to an 8-bit (1-byte) value and stuffed into a 64-bit (8-byte) data transmission variable. This data transmission variable is the characteristic value for biometric data in the Ohio BAN GATT structure. This data is transmitted via a Bluetooth antenna to a central device where it is unpackaged, converted, and displayed to a user in an application. The Enhanced Ohio BAN system is extremely energy efficient since it
sends only one 8-byte value over BLE, for each transmission every 1000 ms (1 second). Additional services and characteristics supporting more BAN functions can be added to the Ohio BAN profile.

Other Sensors

Using the expansive I²C-bus, many more sensor devices can easily be added to the Enhanced Ohio BAN system for a variety of applications. For example, the implementation of new biomedical sensors could open system capabilities to perspiration sensing, respiration monitoring, diabetic health management, stroke detection, and distributed heart rate monitoring.

Using the same or equivalent sensors to the Enhanced Ohio BAN system, advanced biomedical sensing can be achieved. For example, the HTU21D-F digital thermometer can also support relative humidity sensing [27]. This could be used for perspiration monitoring of a wearer. Additionally, the HRM interface could be substituted for another system, such as a distributed heart rate sampling system using a network of heart rate sensors worn directly on the user’s skin. With a distributed heart rate monitoring system in place, the MCU device could handle various readings across the sensor nodes of the network for better accuracy and greater analysis.

Oxygen saturation and carbon dioxide concentration tracking could be added to the system to provide additional biometric data. This could benefit analysis of a patient’s respiratory system as discussed in [32]. Additionally, concentration of glucose in the blood could be monitored using a glucometer device [33]. This could benefit patients who rely on glucose data for personal diabetic health management. Finally, a temperature
sensor mounted directly to the skin could be used to assess acute stroke by sensing
temperature increases and coupling with fall detection data. [34].

Furthermore, the Enhanced Ohio BAN system could be utilized for non-health
related environmental monitoring applications. The Enhanced Ohio BAN system could
be deployed to detect gas or particles in the atmosphere in security systems. For example,
carbon dioxide, oxygen, humidity, and temperature sensors could be used to assess
potentially dangerous environments [35]. The Enhanced Ohio BAN system can benefit
research and development in many potential applications and configurations through the
use of sensors which contain a digital communications interface such as I²C protocol.

Hardware Implementation

Each sensor device requires special preparation for implementation. First, the
HRMI board contains configurable jumpers which can control its operational features
[13]. The jumpers are installed by soldering its respective connection pads together. In
order to configure the HRMI as an I²C device, jumper SJ1 must be installed.
Additionally, jumper OP0 should be installed to operate the HRMI at its maximum I²C
transfer rate of 100 kHz. Jumpers OP1 – OP7 configure the 7-bit I²C address of the
device, where OP1 is the least-significant bit [13]. For the Ohio BAN system, jumpers
OP0 and OP1 are installed, thus equating to the I²C address of the HRMI to be “0x126”.

In order to operate the ADXL345 in I²C mode, the Chip Select (CS) pin is tied
high to the voltage source (i.e., 3.3-V). Additionally, with the Serial Data Output (SDO)
pin tied high, the 7-bit I²C address for the device is “0x1D”. Finally, the HTU21D-F has
a fixed I²C address of “0x40” [14]. All I²C commands to sensors issued by the nRF52832 in the Ohio BAN system will be addressed to each sensor’s respective 7-bit I²C address.

The I²C-bus specification and user manual states that it is necessary to use pull-up resistors on the I²C-bus lines to ensure the SDA and SCL are at readable logic levels. In order to determine pull-up resistor sizing, one must take into account the total bus capacitance. As the number of sensor devices on the line increases, the bus capacitance also increases [26]. The pull-up resistor size $R_p$ is calculated using equation (2) below where $t_r$ denotes the maximum rise time for both the SDA and SCL signals and $C_b$ denotes the total bus capacitance. Typical values for maximum rise time and bus capacitance are given as 1000 μs (microseconds) and 10 pF (picofarads), respectively in the I²C-bus specification and user manual [26].

$$R_p(\text{max}) = \frac{t_r}{0.8473 + C_b}$$  

(2)

The actual bus rise time and capacitance of the Enhanced Ohio BAN system are unknown, but the recommended pull-up resistor size for each respective device is nominally 4.7 KΩ, defined by each device’s datasheet specification [13]-[14], [27]. However, bench testing determined the pull-up resistor size for the Enhanced Ohio BAN system to be 2 KΩ. Figure 14 shows the enhanced Ohio BAN system wiring diagram.
As shown in figure 14, the Enhanced Ohio BAN system relies on a common 9-V battery for its power supply. The voltage is regulated to 5-V using a L7805 voltage regulator and inputted into the nRF52 DK through its micro-USB port. Supply voltage and ground to the sensors are provided through the nRF52 DK edge connectors. The SDA and SCL lines are defined in the device firmware to operate on pins 26 and 27, respectively, on the nRF52 DK.

The system was consolidated to minimize its size by using American Wire Gauge (AWG) size 30 wiring for its power and digital lines. The extra pin holes on the HRMI board were utilized to mount both the ADXL345 and HTU21D-F boards with pin headers. Figure 15 shows this along with the nRF52 DK beneath the sensors. This close configuration allows the system to be compact and easily worn on the body.
A clear plastic case encloses the Enhanced Ohio BAN as shown in figure 16. The device contains a switch to power up the device located at the top of the enclosure. For wireless communications, a specialty SWF-to-SMA adaptor cable is connected to the nRF52 DK’s SWF RF connector, with an SMA female connector protruding from the side of the enclosure for external antenna solutions shown on the right of Figure 16.
Figure 16 - The Enhanced Ohio BAN system inside a clear plastic enclosure with power switch and SMA female connector for external Bluetooth antenna options

**Bluetooth Antenna Considerations**

One of the major benefits of using the nRF52 DK is its versatility for Bluetooth antenna solutions. In addition to an on-board monopole antenna on its PCB, the nRF52 DK includes a small microwave SWF-series surface mount switch RF connector. The SWF RF connector contains an internal switch which can be activated by plugging in a low-cost SWF-to-SMA cable, sending RF signals through the SWF connector and not the on-board monopole antenna. This opens the possibility for other antenna solutions using an SMA connector input to the RF front-end. Moreover, the SWF connector provides a low RF signal loss of 1.0 dB at 2.44 GHz [36].
Nordic nRF52 DK PCB Monopole Antenna

For simplicity, it would be beneficial to implement an antenna solution on the same PCB as the nRF52832 SoC radio module. The nRF52 DK provides a quarter-wave monopole antenna that accomplishes this. The monopole antenna is useful for prototyping Bluetooth applications concurrently while developing software, and it could be reproduced on a downsized nRF52832-based PCB. The monopole antenna provides effective coverage in short range applications which can include body area networks. Figure 17 shows the monopole antenna trace on the edge of the nRF52 DK, as well as the small microwave SWF-connector for external antenna solutions.

Figure 17 - nRF52 DK printed monopole antenna and SWF RF connector
Ohio BAN Patch Antenna

As introduced previously, the Ohio BAN patch antenna is a viable option for wearable applications due to its small size and excellent radiation characteristics. It was specifically designed to direct its radiation pattern away from the lossy human body, as shown in the CEMs and anechoic chamber testing results [12]. As discussed in section 2.4.3, the patch antenna is made wearable by using an elastic chest strap holder, worn similarly to the Polar T31C coded chest strap.

E-Textile Spiral Antenna

For body area networks, fabric based antennas are attractive due to their flexibility, lighter weight, and low cost. For this thesis, the Enhanced Ohio BAN system utilized an e-textile spiral antenna for data collected which was previously created through internal Ohio University research and development.

The Enhanced Ohio BAN system can benefit from the e-textile edge-fed wideband spiral antenna because it supports frequencies in the 2-6 GHz band, including the ISM bands of 2.4 GHz (e.g., 2.4-2.4835 GHz) [37], and has potential to support the 5.8 GHz ISM and WiMax (3.6 GHz) band. Spiral antennas are traditionally center fed perpendicular to the antenna plane, but an edge fed solution is desired in order to be less intrusive to the wearer [37]. Figure 18 shows the e-textile edge-fed spiral antenna that was tested for the Enhanced Ohio BAN system. The antenna is stabilized on a half-inch green foam board, but the final antenna system could be sewn into a wearer’s garment. While the e-textile spiral antenna exhibits different radiation characteristics than the Ohio
BAN patch antenna, it is suitable to support a communications link with a smaller functioning range, such as a body area network [38].

Figure 18 - Edge-fed e-textile spiral antenna worn on the body with supporting foam board underneath

Android Application Development

The Enhanced Ohio BAN system uses a newly developed Android application to display biometric data. The application was designed using Android Studio version 2.3 and programmed onto a Google Nexus 5 smartphone running Android OS 4.4.4 KitKat. The redeveloped application adds BLE GATT functionality for receiving data from the Enhanced Ohio BAN system, as well as a new user interface.

Figure 19 below shows the initial screen upon opening the Enhanced Ohio BAN application. The application prompts the user for permission to turn on the phone’s
Bluetooth functionality, then searches and populates a list of available Bluetooth devices. The application searches for Bluetooth devices for a total of five seconds, which can be changed in software. The user has the option to stop a search or scan for devices again once the search has completed. The RSSi message (in dBm) is shown next to each corresponding Bluetooth device, as seen in Figure 19.

Figure 19 - Ohio BAN application screenshot listing available Bluetooth devices and their RSSi value
A Bluetooth device may be connected by selecting it from the list in Figure 19. A connection is established immediately, and the application navigates the user to the Enhanced Ohio BAN biometric information page as shown in Figure 20. At the top of the screen, the connection status is listed and the GATT profile is shown underneath. Here, a user can select the Enhanced Ohio BAN Service from the list, and view the Biometric Data service which is the profile characteristic listing data values received. Upon selecting this characteristic, the biometric data is populated for each parameter in real time as the information is received from the Enhanced Ohio BAN system. The application displays the heart rate of the user, the ambient temperature, and accelerometer relative position data. The fall detection log featured in the Baseline Ohio BAN system was omitted due to the focus of more substantial upgrades, but it could be included in later versions of the Enhanced Ohio BAN system.
Figure 20 – Enhanced Ohio BAN application showing biometric data received from the connected Ohio BAN system
CHAPTER 5: RESULTS AND DISCUSSION

System Level Testing

Overall performance of a BAN system can be numerically characterized using two primary metrics: the strength of the link between the system transmitter and the smartphone receiver, and the overall power consumption of the system. While size and cost are also important aspects of system performance, they were not the focus of this thesis. The data link strength and power consumption parameters were estimated for the Enhanced Ohio BAN system and compared with the Baseline Ohio BAN system to determine the overall system quality.

Power Received Measurements and Comparisons

The Enhanced Ohio BAN system was operationally tested using the Nordic nRF52 DK printed monopole antenna, the Ohio BAN patch antenna, and an e-textile spiral antenna. Tests were conducted inside the Ohio University Anechoic Chamber, with no other personnel inside except the smartphone operator who wore the Enhanced Ohio BAN system. The operator used a plastic pen and paper to take measurements for the same test scenarios defined in the 2015 IEEE AP-S Student Design Contest: with the phone 1 m in from of the body, in the front pocket, and in the rear pocket. The power received measurements for the Enhanced Ohio BAN system were compared with the same data from the Baseline Ohio BAN system found in [38].

The Bluetooth 4.0 Core specification characterizes the BLE receiver sensitivity as the signal level at the receiver for which a raw Bit Error Rate (BER) of 0.1% is met [39]. This equates to a receiver sensitivity greater than or equal to -70 dBm, which is desired...
for a stable BLE connection. Additionally, the accuracy of the RSSi message defined as ±6 dBm [40]. These parameters will be used to assess the quality of the datalink provided by the Enhanced Ohio BAN system.

The power received measurements for the Baseline Ohio BAN system are shown below in Table 5.1.1a [38]. The previous system was operationally tested inside the Ohio University Anechoic Chamber in the same manner as described above (i.e., no other personnel present, repeat test scenarios). Measurements were taken with the Ohio BAN patch antenna and the e-textile spiral antenna with both mounted to the user’s chest and connected to the system using an RF cable. (Due to the Baseline system’s hardware component selection, the printed monopole antenna was not available for testing). Ten measurements were averaged to determine the overall quality of the system.

Table 1 - Baseline Ohio BAN system RSSi Power Received Measurements by Smartphone

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Baseline Ohio BAN Power Received by Smartphone, [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 m in Front-Torso</td>
</tr>
<tr>
<td></td>
<td>patch  e-textile</td>
</tr>
<tr>
<td>2</td>
<td>-35     -51</td>
</tr>
<tr>
<td>3</td>
<td>-33     -49</td>
</tr>
<tr>
<td>4</td>
<td>-34     -48</td>
</tr>
<tr>
<td>5</td>
<td>-36     -49</td>
</tr>
<tr>
<td>6</td>
<td>-35     -51</td>
</tr>
<tr>
<td>7</td>
<td>-35     -51</td>
</tr>
<tr>
<td>8</td>
<td>-34     -47</td>
</tr>
<tr>
<td>9</td>
<td>-35     -47</td>
</tr>
<tr>
<td>10</td>
<td>-34     -52</td>
</tr>
<tr>
<td>AVG</td>
<td>-34.7   -49.3</td>
</tr>
</tbody>
</table>
The Baseline Ohio BAN system performed favorably for both antenna types analyzed, but the Ohio BAN patch antenna was clearly advantageous due to its higher power received values when the smartphone was in 1 m in front of the torso as well as in the user’s front pocket. On average, the patch antenna produced power received measurements of nearly 15 dBm more in front of the torso and 12 dBm more in the front pocket. This can be attributed to the patch antenna’s utilization of a ground plane which directs the antenna’s radiation pattern in a more forward direction away from the user’s body compared to the e-textile spiral antenna which does not contain any additional material between the textile and the user’s skin.

The back pocket test scenario for the Baseline system produced nearly identical results for both antenna solutions. This can be attributed to the difficulty of transmitting wireless signals surrounding the lossy human body. The average back pocket results suggest potential connectivity issues based on the Bluetooth 4.0 Core specification receiver sensitivity recommendation of -70 dBm, but the measured values are mostly well within the ±6 dBm RSSi message accuracy, and a stable connection is still believed to be possible here. All measured values were better than the specified BLE sensitivity of -87 dBm for the nRF8001 DK [16].

The Enhanced Ohio BAN system power received measurement results are shown below in Table 5.1.1.b. Again, ten measurements were averaged to assess the quality of the system using different Bluetooth antenna solutions. The same patch and e-textile antennas were used as in the Baseline Ohio BAN system (i.e., mounted to the user’s chest), but the nRF52 DK printed monopole antenna was also tested which is housed
inside the Enhanced Ohio BAN system enclosure. The monopole antenna was enabled by unplugging the SWF-to-SMA RF cable located inside the enclosure, thus switching allowing RF signals to bypass the on-board SWF connector.

In Table 5.1.1.b, the row labeled “DIFF” represents the difference in average performance from the Baseline Ohio BAN system (listed in Table 5.1.1.a) to the Enhanced Ohio BAN system (listed in Table 5.1.1.b). Since the monopole antenna was not utilized in the previous system, the difference in performance is unavailable.

Table 2 - Enhanced Ohio BAN system RSSi Power Received Measurements by Smartphone

<table>
<thead>
<tr>
<th>Test Number</th>
<th>1 m in Front-Torso</th>
<th>Front Pocket</th>
<th>Back Pocket</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>patch</td>
<td>e-textile</td>
<td>mono-pole</td>
</tr>
<tr>
<td>1</td>
<td>-36</td>
<td>-61</td>
<td>-61</td>
</tr>
<tr>
<td>3</td>
<td>-40</td>
<td>-71</td>
<td>-58</td>
</tr>
<tr>
<td>5</td>
<td>-38</td>
<td>-55</td>
<td>-58</td>
</tr>
<tr>
<td>6</td>
<td>-37</td>
<td>-57</td>
<td>-57</td>
</tr>
<tr>
<td>7</td>
<td>-40</td>
<td>-60</td>
<td>-60</td>
</tr>
<tr>
<td>8</td>
<td>-39</td>
<td>-59</td>
<td>-60</td>
</tr>
<tr>
<td>AVG</td>
<td>-38.9</td>
<td>-60.3</td>
<td>-59.2</td>
</tr>
<tr>
<td>DIFF</td>
<td>-4.2</td>
<td>-11</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The Enhanced Ohio BAN system produced satisfactory results for all three Bluetooth antenna solutions tested. Similar to the Baseline system, the Ohio BAN patch antenna performed best both 1 m front of the torso and when the smartphone was in the
front pocket. The Nordic printed monopole antenna also produced acceptable results
given its location inside the system enclosure worn on the user’s hip. While the monopole
performed similarly to the e-textile antenna for the test scenario 1 m in front of the human
body, its proximity to the user’s front pocket provided additional power received which
rivaled the proficiency of the patch antenna. All three antenna types provided similar
measurements for the test scenario in the user’s back pocket. Again, all were estimated to
be close to the minimum -70 dBm specified receiver sensitivity minimum to provide a
Bluetooth stable connection; however, the actual sensitivity of the nRF52832 BLE
transceiver was -96 dBm, which is much better than the minimum specified value.

The Enhanced Ohio BAN system provided comparable results versus the Baseline
system. The differences between the measurements were mostly miniscule, but the
Enhanced system estimated a worse performance for the 1 m in front of the torso and
back pocket scenarios, by several dBm for both the patch and e-textile antennas. Little to
no difference was recognized in the front pocket scenario. The difference in performance
can be attributed to the transceiver system, as the same smartphone was used to take
measurements for both systems. The RF cable losses also add some signal degradation,
but the differences noticed are mostly within the ±6 dBm RSSi message accuracy, and all
measurements were above the minimum sensitivity rating of the nRF52832 Bluetooth
radio module of -96 dBm meaning a stable connection is possible for both systems.

*Power Budget Analysis*

The quality of a BAN system can also be assessed by the overall battery lifetime
of the system. The BAN system components contribute to the battery lifetime based
current consumption by each component. The Baseline Ohio BAN system power budget is shown below in Table 5.1.2.a, with the current consumption for each component listed as defined by their respective datasheets [13]-[15], [41] [42].

Table 3 - Baseline Ohio BAN system Current Consumption Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL345</td>
<td>0.150 mA</td>
</tr>
<tr>
<td>HRMI</td>
<td>30 mA</td>
</tr>
<tr>
<td>DS18B20</td>
<td>1.5 mA</td>
</tr>
<tr>
<td>Arduino Uno R3</td>
<td>80 mA</td>
</tr>
<tr>
<td>nRF8001 DK</td>
<td>12 mA</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>123.65 mA</strong></td>
</tr>
</tbody>
</table>

The Baseline system relied on a 9 Volt Alkaline battery with a rating of 550 milliamp Hours (mAH) or 550 mA for 1 hour [43]. The battery lifetime for the Baseline system can be calculated as follows:

\[ \text{Baseline Ohio BAN system Battery Lifetime} = \frac{550 \text{ mA}}{123.65 \text{ mA}} = 4.45 \text{ Hours} \]

The Baseline system relied on both the Arduino microcontroller and the nRF8001 DK adaptor for BLE transmissions which contributed greatly to the total current consumption. On the other hand, the Enhanced system requires less current draw due to more efficient components. Table 5.1.2b shows the current consumption for each component as well as the total current consumption for the system as a whole.
The Enhanced system uses almost one fourth of the total current required by the Baseline system. Similar to the Baseline system, it also relies on a 9 Volt Alkaline battery with a rating of 550 mAH. The battery lifetime for the Enhanced system can be calculated as follows:

\[
Enhanced \ Ohio \ BAN \ system \ Battery \ Lifetime = \frac{550 \ mA}{35.9 \ mA} = 15.3 \ Hours
\]

The Enhanced Ohio BAN can function nearly four times as long using the same battery over the Baseline system. This is attributed to using more power efficient technology, most notably the nRF52 DK which only draws 5.3 mA peak current in BLE transmission at 0 dBm [29].

The Enhanced Ohio BAN system can further be optimized for low power consumption by eliminating the HRMI board which draws a maximum of 30 mA due to its advanced functionality and on-board firmware for processing heart rate data. The heart rate data could theoretically be processed using the nRF52832 SoC, or a more efficient heart rate module could be selected. Another factor which influences power consumption is data update rate. The Enhanced Ohio BAN system was programmed to take sensor measurements and transmit Bluetooth data every 1000 microseconds, and this time period could be extended in order to optimize power consumption.

Table 4 - Enhanced Ohio BAN system Current Consumption Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Supply Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL345</td>
<td>0.150 mA</td>
</tr>
<tr>
<td>HRMI</td>
<td>30 mA</td>
</tr>
<tr>
<td>HTU21D-F</td>
<td>0.450 mA</td>
</tr>
<tr>
<td>nRF52 DK</td>
<td>5.3 mA</td>
</tr>
<tr>
<td>TOTAL</td>
<td>35.9 mA</td>
</tr>
</tbody>
</table>
CHAPTER 6: CONCLUSION

An Enhanced Body Area Network was designed to offer better adaptability into emerging remote healthcare monitoring applications in order to mitigate the rising trends of disease and healthcare costs. The focus of this thesis project was to upgrade the core units of the previously award-winning Ohio Body Area Network system to address several limitations and lay a foundation for future development. The upgraded Enhanced Ohio BAN system focused on each device subsystem including the biometric sensors, the microcontroller, the Bluetooth antenna, and the smartphone application.

The biometric sensors were unionized using the I²C-bus with the addition of the HTU21D-F temperature sensor. This will allow for a simpler firmware setup and eliminates excess wiring. The Arduino microcontroller was replaced with the powerful Nordic nRF52832 SoC, which boasts a smaller form-factor and its own built-in Bluetooth radio module. The BLE stack was updated by utilizing a full GATT profile. The new profile uses services and characteristics to transmit biometric data from the microcontroller to the smartphone which allows for greater efficiency and simplicity.

Enhancements were also tested for the Bluetooth antenna with the incorporation of an e-textile spiral antenna and a printed monopole antenna on the Nordic nRF52 development kit. Anechoic chamber testing proved that both antenna types as well as the Baseline patch antenna provided working results for the Enhanced Ohio BAN within the Bluetooth band. The Enhanced system also provided excellent power efficiency over the Baseline system, reducing the estimated current consumption from 123.65 mA to 35.9
mA and providing approximately 10 more hours of battery life using a typical 9 V battery.

Finally, the Android smartphone application was redesigned to cooperate with the Enhanced system. The generic attribute profile was utilized to share biometric data between the Ohio BAN system and the smartphone. Biometric data is displayed to the user and updated continuously every second. Altogether, the Enhanced Ohio BAN system improvements lay the groundwork for future development in BAN applications which could potentially reduce the rates of disease, injuries, and fatalities as well as slowing the trend of rising healthcare costs.
CHAPTER 7: RECOMMENDATIONS FOR FUTURE WORK

Further research should focus on expanding the operations of the Ohio BAN system. Additional sensors may be added to develop the capabilities of the system as a remote healthcare monitoring device. For example, additional sensors could be interfaced for perspiration observations by adding relative humidity readings from the HTU21D-F sensor. Respiratory monitoring could be implemented by including Oxygen and Carbon-dioxide sensors to monitor a user’s breathing. Diabetic health management could be applied using blood-glucose sensors implanted inside a user’s body. Acute stroke assessments could utilize fall-detection data from the ADXL345 accelerometer board coupled with heart rate information, and advanced heart rate sensing could be fulfilled using a distributed network of heart rate monitoring sensors placed on the body.

Further, additional sensors may provide environmental data for safety purposes. New sensors may be added to the same I^2C-bus utilized by the Enhanced Ohio BAN system, which in total can support 128 sensor devices.

The system as a whole could be downsized into a single printed circuit board. While the nRF52 development kit supports many advanced features, most go unused in the Ohio BAN system. The small form factor of the nRF52832 SoC makes it ideal for placement on the human body with minimal intrusion. Coupled with printed electronics and a wearable antenna solution, the Enhanced Ohio BAN system could offer superior biometric sensing while being unnoticed by the wearer, thus making it ideal for accurate patient monitoring and analysis.
REFERENCES


[14] 3-axiz, ±2 g/±4 g/±8 g/±16 g Digital Accelerometer - ADXL345, Rev. 0, Analog Devices, Inc., Norwood, MA., 2009.


[40] *Specification of the Bluetooth system experience more core system package version 4.0*, vol. 2, pp. 687, June 2010.


