PERFORMANCE ANALYSIS OF WIRELESS SENSOR NETWORKS IN GEOPHYSICAL SENSING APPLICATIONS

by

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ABSTRACT

Performance is an important criteria to consider before switching from a wired network to a wireless sensing network. Performance is especially important in geophysical sensing where the quality of the sensing system is measured by the precision of the acquired signal. Can a wireless sensing network maintain the same reliability and quality metrics that a wired system provides?

Our work focuses on evaluating the wireless GeoMote sensor motes that were developed by previous computer science graduate students at Mines. Specifically, we conducted a set of experiments, namely WalkAway and Linear Array experiments, to characterize the performance of the wireless motes. The motes were also equipped with the Sticking Heartbeat Aperture Resynchronization Protocol (SHARP), a time synchronization protocol developed by a previous computer science graduate student at Mines. This protocol should automatically synchronize the mote’s internal clocks and reduce time synchronization errors. We also collected passive data to evaluate the response of GeoMotes to various frequency components associated with the seismic waves.

With the data collected from these experiments, we evaluated the performance of the SHARP protocol and compared the performance of our GeoMote wireless system against the industry standard wired seismograph system (Geometric-Geode). Using arrival time analysis and seismic velocity calculations, we set out to answer the following question. Can our wireless sensing system (GeoMotes) perform similarly to a traditional wired system in a realistic scenario?
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CHAPTER 1
INTRODUCTION

The rapid adoption of wireless sensor networks (WSNs) in several applications is due to various practical reasons. The main reasons include the ease of deployment, ability to operate in harsh environments, high levels of reliability, and solid performance. Due to their distributed nature and the ability to collaborate, WSNs can sometimes sense events that ordinary systems cannot.

As an example, if a single soil moisture sensor is deployed in the field, we can learn about the soil moisture at that point. If we increase the number of sensors deployed, distributing them across a wider landscape, an entire topography of the soil moisture emerges, i.e., we obtain a holistic view of soil moisture variations in that landscape. In short the data collected from a distributed WSN can be used to monitor and possibly improve the system in which the WSN is deployed.

Our work focuses on analyzing the performance of a novel wireless geophysical sensing system against the industry standard, i.e, a wired Geometric-Geode sensing system. We devised and deployed a set of experiments to compare a set of wireless sensor motes that were developed by former computer science graduate students, namely GeoMote, against the traditional wired system. We, thereby, gained key insights into how this novel system performs when deployed in the field.

Chapter 2 provides a background on wireless sensor networks and their classification based on application objectives and data delivery requirements. It also presents the reader with a high-level view of sensor mote design and the rationale behind its development. Lastly, Chapter 2 introduces ideas on how these wireless motes can be used for various geophysical applications, such as earth, dam, and levee health monitoring.
Chapter 3 explains our experiment design, e.g., the sensor layouts and wireless network configurations used in the GeoMotes. We also provide a detailed account on how our WalkAway and Linear-Array experiments were carried out in the field. Lastly we discuss our data collection mechanisms that were used by the data acquisition systems.

Chapter 4 provides our results and analysis from our WalkAway experiment. We analyze the performance of our wireless sensing system with respect to three performance metrics, i.e., accuracy, precision, and time synchronization. We then compare the wireless system results with a traditional wired system. We also perform a power spectral analysis of the data acquired from the wireless GeoMote WSN. To provide insight into how a wired GeoMetric-Geode performs in a WalkAway test, we include results from analyzing wired data from a previous WalkAway experiment. We conclude the chapter by summarizing the findings from our WalkAway experiment.

Chapter 5 presents the results and analysis from our Linear Array experiment. We first summarize the signal processing completed to prepare the data for analysis, as well as explain the process of picking time zero (T0). We analyze the arrival time for the shot-receiver pairs for both systems and perform seismic velocity calculations and tomography modeling. We analyze accuracy by calculating the normalized root mean square error between the data acquired by the wired Geometric-Geode and the data acquired by the wireless GeoMote WSN. The chapter also includes results from amplitude and passive data analysis, which provides critical insights into the wireless GeoMote WSN’s performance. We conclude the chapter by summarizing the findings from our Linear Array experiment.

In Chapter 6, we provide concluding remarks and propose future work. That is, we summarize our findings and propose the next set of experimentations that should be completed to perform further field evaluations of the wireless GeoMote system. We also outline the limitations of the GeoMotes and methods that may improve their performance and ease of use in the future.
CHAPTER 2
BACKGROUND

Seismology is the scientific study of the propagation of elastic waves through the earth or physical structures. To study the events caused by the propagation of elastic waves, seismometers are used. Seismometers contain geophone sensors that measure and record the motion of elastic waves as they pass through the subsurface.

A geophone sensor is a passive analog device that converts ground displacement into voltage readings. The voltage response of the geophone is proportional to the ground velocity of the waves. Geophones are a key component of any geophysical sensing system. A wireless geophysical sensor mote has a microcontroller with a high resolution ADC that is interfaced to a geophone sensor. The motes also have a radio that is used to receive commands from the base station and to transmit the data collected from the geophone sensors.

A group of wireless sensor motes connected to a base station constitute our wireless sensor network (WSN). Formally, a WSN is a collection of densely deployed sensing components that can sense and/or monitor various events over a period of time. WSNs also have the capability of performing limited computations on the acquired data and transmitting the data to the base station. WSNs can be broadly classified into three categories [1], as we discuss next.

**Event detection and reporting:** This type of WSN system deals with infrequent events of interest. Thus, the system may be inactive for a long period of time, and then suddenly burst into life when an event has been detected. Examples of such systems include intruder detection and forest fire detection.

**Data gathering and periodic reporting:** In this type of WSN system, the sensors are expected to periodically collect data that is then transmitted to the back-end system (sink). The back-end system (sink) might not be directly interested in this data, but could perform
some sort of distributed computation on the sensor readings to obtain the data desired.

**Sink-initiated querying:** This type of WSN has an additional functionality where the base station queries individual sensor motes for data rather than the sensor mote reporting the measurements periodically. Our work falls into this category, which can be used for various geophysical sensing applications such as earth, dam, and levee (EDL) anomaly detection and health monitoring.

EDL health monitoring is an important application of WSNs, as the age of many dams in the U.S. is more than 60 years [2]. Thus, structural failures can occur due to instability, piping, foundational issues, or internal erosion. Timely detection of these events is both difficult and resource consuming due to the inherent complexities of these structures. Although these challenges exist, a geophysical WSN is a good choice as it provides a cost effective solution that is robust yet efficient.

To create a wireless geophysical sensing system, our SmartGeo colleagues designed a custom mote (gsMote); the gsMote has an Atmel AVR XMEGA256A processor, 24-bit ADC, 64KB SRAM, and 32GB SD Storage. Figure 2.1 shows the initial gsMote prototype inside a waterproof enclosure.

![Figure 2.1: Initial gsMote prototype [3].](image)

This first generation mote took a long time to develop and was not well documented nor easy to use “out of the box” [3]. To address these difficulties, more recent SmartGeo colleagues developed a second generation geophysical sensing mote (GeoMote) based on the Arduino platform. The Slim GeoMote has a 24-bit ADC and 32KB external SRAM;
the Standard GeoMote also includes GPS and a microSD card socket. Figure 2.2 shows a prototype of the GeoMote.

There were several reasons to choose an Arduino platform for building the second generation geophysical mote [3]. First, all Arduino-based platforms use high-level C++ APIs, which abstracts much of the low-level programming of embedded systems. Second, Arduino platforms are 100% open source and there exists an extensive online support community. Because of these reasons, it is easier to integrate new features to the platform. Lastly, Arduino Fio has an XBee radio socket that allows users to experiment with radios of varying range, i.e., choose a range required by the application.

![GeoMote platform](image)

**Figure 2.2: GeoMote platform [3].**

<table>
<thead>
<tr>
<th>Sampling Rate (Hz)</th>
<th>Waveform Frequency (Hz)</th>
<th>Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>5</td>
<td>sine, square, triangle</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>sine, square, triangle</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>sine, square, triangle</td>
</tr>
<tr>
<td>1000</td>
<td>50</td>
<td>sine, square, triangle</td>
</tr>
</tbody>
</table>

Table 2.1: Lab test waveform summary.

For validating the GeoMotes, controlled lab tests were conducted using a WSN of nine GeoMotes, such that the data was collected from a voltage signal generator. Three different types of signals (i.e., sine, square and triangle waves) were sampled by the motes with 24-bit precision at various sampling frequencies (i.e., 100, 250, 500 and 1000 Hz). When the motes
were sampling at 100 or 250 Hz, the test signal was generated at 5 Hz; when the sampling was performed at 500 or 1000 Hz, the test signal was generated at 50 Hz.

Table 2.1 summarizes the sampling rates, waveforms, and their frequency in the lab tests. The accuracy of the GeoMote ADC’s clock was confirmed by analyzing the acquired sine wave in the frequency domain. For each of the four sampling rates evaluated, the acquired signals were stacked by summing them together and subtracting the mean to remove the DC component. A 512-bin FFT was computed and a visual inspection of the acquired signals in the frequency domain (Figure 2.3 (a) and Figure 2.3 (b)) confirmed that the acquired signals were close to the target frequencies. These results are from version 2 of the GeoMotes, but we expect they would be the same for version 3 of the GeoMotes.

![Figure 2.3: Normalized frequency magnitudes of a 512-bin FFT for 5 Hz and 50 Hz sine waves [3].](image)

In the work presented herein, we used version 3 of the GeoMote. GeoMote V3 provides an improved design, by utilizing surface-mounted components and including a triaxial accelerometer sensor and a temperature sensor. Compared to GeoMote V2, GeoMote V3 also has a dedicated power switch and programming port; in addition, the layout and routing was improved to reduce noise and adopt a smaller form factor for ease of use. Figure 2.4 shows the GeoMote V3 and its main components - the lithium-ion battery, XBee Pro radio,
ADC input ports, and the Arduino Fio board. Figure 2.5 shows the GeoMote V3 platform connected to a geophone sensor.

In our work, the GeoMotes V3 were also equipped with the Sticking Heartbeat Aperture Resynchronization Protocol (SHARP) [15]. The goal of SHARP is to reduce the time synchronization errors in a WSN while overcoming the shortcomings of existing protocols.
SHARP requires very few synchronization messages to be transmitted in the network, thus providing an efficient and light-weight solution to the time synchronization problem faced by wireless sensor networks.

![Wired Geometric-Geode seismic system with seismic cable and geophones](image)

Figure 2.6: Wired Geometric-Geode seismic system with seismic cable and geophones [8].

The wired system that we used for our comparison study is called the Geometric-Geode seismic recorder system, which is the best system in the industry for refraction/reflection and tomography surveys. The Geode seismic system can house 3 to 24 channels and weighs 8 lbs. Figure 2.6 shows the instrument connected to a laptop. The Geometric-Geode seismic system is a 24-bit high resolution data collection system supporting up to 20 KHz bandwidth (8 to 0.02 ms sampling) with extremely low noise and distortion (0.0005%). The geophone sensors are connected to the seismograph in a series using the seismic cable. When the system is triggered (e.g., by a hammer impact on a metal plate), it starts recording seismic data continuously and saves the data on the system. The system is also used for monitoring earthquakes, quarry blasts, and vibration from heavy equipment.
CHAPTER 3
EXPERIMENTAL SETUP

In this section we describe the experiments we conducted to evaluate our wireless sensor network against the Geometric-Geode wired system. These experiments were in collaboration with a geophysics expert from the United States Bureau of Reclamation and a former Ph.D. student at Colorado School of Mines. We also outline the radio configurations used along with the data collection mechanism adopted for these experiments.

3.1 Radio details and configuration

The motes and the base station were equipped with XBee-Pro radios. Each radio on a mote is an XBee 2 mW Whip Antenna; the base station radio is a 2.4 GHz Duck Antenna with an RP-SMA connector for improved data reception.

Table 3.1: XBee Radio configuration used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAN ID</td>
<td>1234</td>
<td>Personal Area Network Identifier</td>
</tr>
<tr>
<td>Channel</td>
<td>0x17</td>
<td>Channel in the 2.4GHz 802.15.4 band</td>
</tr>
<tr>
<td>Baud rate</td>
<td>57600</td>
<td>Baud rate for serial communication</td>
</tr>
<tr>
<td>RO</td>
<td>10</td>
<td>Radio output packetization timeout</td>
</tr>
<tr>
<td>MY address</td>
<td>0</td>
<td>Address of every mote (Set to 1 for the master)</td>
</tr>
<tr>
<td>DL</td>
<td>0</td>
<td>Destination address to send data to</td>
</tr>
</tbody>
</table>

Table 3.1 provides the parameters that were configured on the XBee radios. The default values were used for all other radio parameters not listed in Table 3.1. We used the XCTU software for programming the radios, which is free from Digi International (the manufacturer of our radios).
3.2 Generic setup for experiments

One main component of the WSN in our experiments was a base station that issued commands to the motes and received the data from the wireless motes in a round robin fashion. To enable and evaluate the time synchronization protocol (SHARP), we deployed a special master that sent periodic heartbeats (every 250 ms) to other motes in the wireless network. We note that the purpose of the master mote was to transmit heartbeats; it did not perform any sensing operations.

Since the radios (including that of the master and the base station) were configured in unicast mode with the same address and channel, the base station had to avoid collisions from sending a base station command during the same time the master was sending a heartbeat packet. We, therefore, configured the base station to send commands to the motes in a 230 ms window (as it takes roughly 20 ms for the heartbeats to be transmitted on the network).

The mote's ability to capture seismic data beyond 60 feet was not practical with the default gain setting of 1. We, therefore, conducted further indoor tests to find the optimum gain required for the 180 feet distance range we were aiming for in our experiments. The optimum gain setting was found to be 32 (out of 1, 2, 4, 8, 16, 32, 64 and 128) after many indoor tests. We also note that the motes had the ability to switch the gain settings ‘live’ during the experiment in the field. Both the wired and wireless systems were set to collect data at 500 Hz sampling rate for all the experiment runs.

3.3 Data collection mechanism

To issue the commands and collect the data from the motes, we followed a sequence of steps that are outlined in Table 3.2. These steps were repeated to collect samples for every shot during the experiment. We switch off the master mote in step 6 to avoid collisions during the transmission of data by the motes.
Table 3.2: Steps for data collection.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turn on the master to start transmitting the heartbeat.</td>
</tr>
<tr>
<td>2</td>
<td>Wait 10 seconds for the network time to stabilize.</td>
</tr>
<tr>
<td>3</td>
<td>Base station sends command - Start sampling.</td>
</tr>
<tr>
<td>4</td>
<td>Wait for the required sampling duration.</td>
</tr>
<tr>
<td>5</td>
<td>Base station sends command - Stop sampling.</td>
</tr>
<tr>
<td>6</td>
<td>Turn off master mote.</td>
</tr>
<tr>
<td>7</td>
<td>Base station sends command - Transmit data.</td>
</tr>
</tbody>
</table>

3.4 Experiment 1: WalkAway

A common geophysical experiment, often called a ‘WalkAway’ test in geophysics, involves placing a group of geophone sensors in a tight cluster with a minimum spacing between them. To create the data that is sampled for each shot, the experimenter uses a sledge hammer to pound a metal plate on the ground. This produces a seismic surface wave that is recorded by the WSN. Figure 3.1 shows the field setup for this experiment. We used a total of eighteen wireless sensor motes that were placed in a tight cluster. A total of seven shots were recorded at various distances, which are summarized in Table 3.3.

![Figure 3.1: WalkAway experiment setup with wireless GeoMote WSN.](image)
Table 3.3: Shot distance from the cluster.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Distance (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
</tr>
<tr>
<td>7</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 3.3 summarizes the distance at which each shot was delivered. The goal of this experiment was to evaluate various parameters of a seismic sensing system. First, this experiment evaluates and characterizes the level of time drift across the wireless network, from calculating the time lags between the sensor motes. Second, it helps to understand the effect of gain settings on the sensitivity of the motes and how they affect the data quality at various shot distances. Third, it verifies the radio range limits and the transmission issues, if any exist, in the wireless network at a given shot distance. Lastly, the results can be used to analyze the power spectrum of the signals received by the wireless motes in order to verify if the signals have similar or comparable frequency contents.

3.5 Experiment 2: Seismic P-wave Refraction Tomography

This experiment, which is commonly called a ‘linear array test’ in geophysics, involves placing an array of geophones at 10 foot offsets. The experimenter uses a sledge hammer to pound a metal plate on the ground, which is adjacent to one of the geophones. The shot delivered is near that sensor, while other sensors in the array ‘receive’ the shot. We used 18 geophone sensors to create an array spanning a distance of 170 feet, and recorded 11 shots at various distances. Figure 3.2 illustrates the setup used in this second experiment, and Table 3.4 summarizes the distance at which each shot was delivered from Sensor 1. The goal of this experiment is to evaluate the wireless sensing system’s capabilities for a full scale refraction survey, to further determine limitations within the wireless system.
Figure 3.2: Seismic P-wave Refraction Tomography experiment setup with wired GeoMetric-Geode system and wireless GeoMote WSN.

Table 3.4: Sensor where shot was delivered and distance from Sensor 1.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Sensor</th>
<th>Distance (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
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<tr>
<td>4</td>
<td>7</td>
<td>60</td>
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<tr>
<td>5</td>
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<td>6</td>
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<td>140</td>
</tr>
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<td>9</td>
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<td>160</td>
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<tr>
<td>10</td>
<td>18</td>
<td>170</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>
Using the data collected from this experiment, tomography models can be constructed for both wired and wireless systems. We manually pick the arrival time for the seismic waves and compare the 2D cross-sectional models of seismic velocity distributions within the subsurface. The experiment can also be used to make a quantitative comparison of several system parameters such as deployment speed, data collection capabilities, accuracy, and precision of the collected data against the industry standard Geometric-Geode wired system.

3.6 Experiment 3: Passive data collection

We collected passive data samples from the wireless system to analyze the frequency response of the system. The system recorded the data for the maximum duration that it was capable of, during which the experimenter generated various seismic events such as sledge hammer impacts or stomping on the ground. As a part of this experiment, we also recorded the seismic data that was generated by distant vehicle movements in order to help us understand the responsiveness of the system to distant vibrations.
CHAPTER 4
RESULTS AND FINDINGS FROM WALKAWAY EXPERIMENT

In this chapter we share our results and findings from the WalkAway experiment we outlined in Chapter 3. This chapter is organized as follows. First, we provide signal processing details on preparing the data for analysis (Section 4.1). Second, we provide the results of data analysis for the WalkAway experiment conducted (Section 4.2). Our results are based on three metrics that are critical in geophysical sensing, i.e., time synchronization, accuracy, and precision. We also provide a power spectrum analysis of the signals acquired. Finally we conclude the discussion summarizing our findings (Section 4.3).

Time synchronization of data collected is critical for geophysical modeling, inversion, and visualization. In geophysics, the time lag between signals is needed to understand the data; these time lags represent the arrival time difference of the seismic waves being measured. We need a sensing system to be capable of accurate time synchronization, such that the lags in the acquired signals correspond to the arrival time difference between the seismic waves (and not due to synchronization errors).

Accuracy measures how capable the wireless sensing system is able to accurately record the seismic events. In other words, accuracy corresponds to how close the data collected from the wireless system is to physical reality.

Precision is a measure of how consistent the wireless sensing system is in acquiring the same type of signal over a period of time. Essentially this metric tries to answer the question: Is the data acquired for a given seismic event the same for all motes?

4.1 Signal Processing

The first step to signal process the acquired data is to convert the ADC values into voltage values. Since each reading provided by the GeoMote is a 24-bit ADC value, we had to convert this value to a voltage via the following three steps [4]:

\[ V = V_{ref} \times \frac{V_{in}}{V_{ref}} \times \frac{V_{scale}}{V_{ref}} \]
1. The ADC range (R) depends on the resolution of the ADC. Since we use a 24-bit ADC [4], the range is given by:

\[ R = 2^{24}. \]  

(4.1)

2. The multiplication factor (M) depends on the reference voltage supplied to the ADC. This value is 1.25V, as we use a voltage regulator [5] to provide a stable reference voltage. Also, since we configure the ADC in differential sampling mode, the reference voltage needs to be doubled. Hence, the multiplication factor is given by:

\[ M = \frac{R}{(1.25 \times 2)}. \]  

(4.2)

3. Given the 24-bit ADC reading (r), we note the range (R) of the ADC is divided by 2 because voltage zero corresponds to the middle value of the range (R). The equation to obtain the resultant output voltage is defined by the equation:

\[ V_{\text{output}} = M \times (r - \frac{R}{2}). \]  

Using Equation 4.3, we converted the GeoMote data collected to output voltage. The next step was to remove the voltage drop-outs from the data which was achieved by filtering the data using a third order median filtering. With the drop-outs removed, we proceeded to normalize the signal in order to have a common scale of zero mean and unit variance (which is a common practice in geophysical signal analysis). Equation 4.4 provides the formula for normalizing the voltage values to have a common scale of zero mean and unit variance, where \( x \) is the sample value and \( x_n \) is the normalized value.

\[ x_n = \frac{x - \text{mean}(x)}{\text{std}(x)}, \]  

(4.4)

4.2 Results from WalkAway Experiment

In this section we provide the results from our WalkAway experiment. We explain our three metrics at the beginning of this chapter; this section provides the results of evaluating each metric. We outline the results from the power spectrum analysis of the acquired signals
for the selected shots. We also provide our results of evaluating the wired system against each metric, using the data from an earlier WalkAway experiment.

For evaluating the accuracy and precision of the WSN for a given shot, we calculated the normalized root mean square error (NRMSE) between the reference signal and the other collected signals in the same shot. NRMSE represents the signal’s error as a percentage of the original signal’s range. It is defined as:

\[
NRMSE = \sqrt{\frac{\text{mean}((x - x')^2)}{\text{max}(x) - \text{min}(x)}},
\]

where \(x\) is the reference signal (Channel 1) and \(x'\) is a given wireless signal. We set a qualifier for the NRMSE evaluation that the median error of a wireless system should be within 5% in order to conclude that the signal accuracy (or precision) of that wireless system is accurate (or precise).

### 4.2.1 Time synchronization

Although we had used the SHARP time synchronization protocol, we observed motes having differences in physical time. We then discovered that SHARP synchronizes logical time, not physical time. Furthermore this logical time was not accounted for in the signal acquisition process. Thus, to perform the signal comparison, we had to align the signals of the wireless system manually and perform a sensor-to-sensor waveform comparison.

The standard approach to align signals in signal processing is a cross-correlation lag calculation between a pair of signals. Cross-correlation indicates the amount of time shift needed for one signal to have maximum correlation with another signal. In a perfectly aligned system, this time shift would be zero.

We aligned all the signals using cross correlation to find the overall lag trend for the shot. For all our alignment calculations, the signal from sensor mote one (Channel 1) was chosen to be the reference signal; the remaining 17 channels were then aligned with respect to this reference channel. For each shot, we first show the signal plots without the alignment, followed by an image that shows the signal plots after alignment. We infer from our reference
signal (Channel 1) of Figure 4.1 that the seismic event (sledge hammer impact) occurred at approximately 3.74 seconds for Shot 1.

We note that the sampling frequency for the motes was configured to be 500 Hz; however, the actual sampling frequency was 505 Hz for all iterations of our experiment. This non-standard sampling rate is the result of integer division and the ADC's oscillator rate. Please refer to the ADC's data sheet for specific details on how the sampling rate is determined [4].

Figure 4.1: Unaligned signals for Shot 1 from the wireless GeoMote WSN.

Figure 4.2: Aligned signals for Shot 1 from the wireless GeoMote WSN.

Figure 4.1 shows that, for Shot 1, signals 2, 3, 4, 5, 7, 8, 9, 10, 14, 15, 16, 18 are lagging behind and signals 6, 11, 12, 13, 17 are ahead of the reference signal (Channel 1). Figure 4.2 indicates the same signals after we align them with respect to the reference signal. From
Figure 4.3: Unaligned signals for Shot 7 from the wireless GeoMote WSN.

Figure 4.4: Aligned signals for Shot 7 from the wireless GeoMote WSN.
Figure 4.5, we infer that the seismic event for Shot 7 occurred at approximately 3.17 seconds. We also note that the signals 11, 12, and 17 are significantly early relative to the reference signal. Figure 4.4 shows the same Figure 4.3 signals aligned with respect to the reference signal. We note that the results from our cross-correlation algorithm were not satisfactory for Shot 7; thus, we manually aligned the signals for Shot 7. We hypothesize that the difficulty in the alignment was due to the noise level associated with the signal. We believe the noise is due to the distance at which the shot was delivered (140 feet for Shot 7 versus 20 feet for Shot 1). This noise is obvious when the signals in Figure 4.1 (Figure 4.2) are compared with Figure 4.3 (Figure 4.4).

Figure 4.5 shows a box plot with the time lags calculated for each signal with respect to the reference signal (Channel 1). The red line is the median, the blue box represents the 25th and the 75th percentiles, the ‘whiskers’ correspond to 2.7σ (where σ is the standard deviation), and the red points are the outliers. We note that the outliers are due to motes
11, 12, and 17, the three motes that were significantly behind the reference channel in all the iterations of our experiment.

4.2.2 Accuracy

Accuracy measures the similarity between the signals acquired for a seismic event. We assume that the reference signal (Channel 1) is the ground truth and, thus, compare the remaining channels with respect to the reference channel. To evaluate the accuracy of our WSN, we calculated the normalized root mean square error (NRMSE) between the seismic events captured with our WSN.

For all eighteen channels for a given shot, we calculated the NRMSE between the reference signal (Channel 1) with each of the other 17 signals from the other motes. The NRMSE calculations were performed after time aligning the 17 signals with the reference signal (Channel 1). We present the NRMSE results from Shot 1 and Shot 7, which were delivered at 20 and 140 feet, respectively.

Figure 4.6 represents the box plot for the NRMSE calculated for each signal with respect to the reference signal from Shot 1 (left) and Shot 7 (right). The red line is the median, the blue box represents the 25th and the 75th percentiles, the ‘whiskers’ correspond to 2.7σ (where σ is the standard deviation), and the red points are the outliers. The accuracy results presented in Figure 4.6 show our median error with the alignment is below 5% for both Shot 1 and approximately 10% for Shot 7. This result indicates that the accuracy of the GeoMote reduces at larger distances. We hypothesize that this reduction in accuracy is due to the noise associated with the signal, which increases the error between the signals. Thus, we conclude that the GeoMotes perform comparably in terms of accuracy. We note that the data from Shot 6, which was at 200 feet, was extremely noisy and hence not used in our NRMSE comparisons. We also note that the other shots have approximately the same NRMSE distribution, with the median NRMSE consistently less than 11%.
Figure 4.6: Box plot showing accuracy NRMSE between signals for Shot 1, aligned (a) and unaligned (b), and for Shot 7, aligned (c) and unaligned (d), from the wireless GeoMote WSN.
4.2.3 Precision

We next calculated the precision of our WSN. This metric represents the reproducibility of the specific data that the system recorded; a system that is precise should record the same signal every time (even if the recorded data is not accurate). Precision is a key metric in geophysical sensing systems, as the differences between multiple time synchronized signals should be due to the triggering of different motes, and not due to the imprecision between the sensor motes.

To evaluate the precision of our WSN, we calculated the NRMSE of signal differences between all unique combinations of signal pairs for each shot. Table 4.1 indicates the combinations used for the NRMSE calculations in our evaluation. For each shot, we calculated the NRMSE for each combination listed in Table 4.1 and then created box plots to represent the results from this analysis. We show the results from Shot 1 and Shot 7 next.

Table 4.1: Combination of signals for NRMSE calculations.

<table>
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<tr>
<th>Signal</th>
<th>Paired Signal</th>
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<tbody>
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</tr>
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</tr>
<tr>
<td>4</td>
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</tr>
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<tr>
<td>16</td>
<td>17,18</td>
</tr>
<tr>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 4.7: Box plot showing precision NRMSE of signal differences for Shot 1 (left) and Shot 7 (right) from the wireless GeoMote WSN.

Figure 4.7 represents the NRMSE box plot for signal differences between the unique combinations represented in Table 4.1 for Shot 1 (left) and Shot 7 (right). As before, the red line is the median, the blue box represents the 25th and the 75th percentiles, the ‘whiskers’ correspond to $2.7\sigma$ (where $\sigma$ is the standard deviation), and the red points are the outliers. We note that the median NRMSE for the signal difference is approximately 5% for Shot 1 and 9% for Shot 7, respectively. We note that the precision results of the wired Geometric-Geode (see Section 4.2.5) is close to 7% for a similar shot distance of 150 feet. This result indicates that the precision is affected by distance resulting in signals being less precise at larger distances for both systems. We infer that our WSN performs reasonably in terms of precision at larger distances. We also note that the other shots have approximately the same NRMSE distribution, with the median NRMSE consistently less than 9%.
4.2.4 Power spectral analysis

Spectral analysis is a widely used technique to estimate the power content associated with frequencies in a given signal. We used a spectrogram to analyze the power contents that was associated with the signals acquired by our motes. A spectrogram provides a time-frequency representation of the signal and plots the frequency variations as a function of time. These variations are color coded, which can be used to decipher the power associated with the signal. Figure 4.8 and Figure 4.9 show the power spectrum of all channels for Shots 1 and 7, respectively.

![Figure 4.8: Power spectrum for Shot 1, all channels, from the wireless GeoMote WSN.](image)

A visual inspection of the spectrograms shows us the maximum power that was associated with the signals from all 18 motes, which we can then use to predict the occurrence of the seismic event. The predicted time frame was then visually verified by comparing with the same seismic event in the time domain (results are presented in Section 4.2.1). For example, in Figure 4.2 the shot occurred at approximately 3.7 seconds and this result can be inferred
Figure 4.9: Power spectrum for Shot 7, all channels, from the wireless GeoMote WSN.

from Figure 4.8 as well. The red color indicates the maximum power associated with the signal, which corresponds to the occurrence of the seismic event. The power spectrum for Shot 7 shows that the signal has a considerable amount of noise associated with it; again, it can be inferred that the shot occurred at approximately 3.1 seconds as indicated by Figure 4.4 and Figure 4.9. The dark red portions of the spectrogram indicate the occurrence of the seismic event.

4.2.5 Results from evaluating the Geometric-Geode wired system

We did not use the wired Geometric-Geode system with our most recent WalkAway test. We, therefore provide insights on its system performance by evaluating the data that we obtained in a previous iteration of the WalkAway test. We present our results from an evaluation of data from four channels of the Geometric-Geode, at shot distances of 20 and 150 feet (which are similar to the shots we evaluated for our WSN). Table 4.2 summarizes the details of the wired system used in the previous WalkAway experiment. Similar to the
WSN evaluation, Channel 1 was used as a reference signal for all evaluations.

Table 4.2: Geometric-Geode details for the WalkAway experiment.

<table>
<thead>
<tr>
<th>Property</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of motes</td>
<td>4</td>
</tr>
<tr>
<td>Distance - Shot 1</td>
<td>20 feet</td>
</tr>
<tr>
<td>Distance - Shot 2</td>
<td>150 feet</td>
</tr>
</tbody>
</table>

The evaluation was performed using the same metrics that were used in the evaluation of the GeoMote WSN, i.e, accuracy, precision, and time synchronization. We share our results after processing the data from both shots next. Figure 4.10 shows the signal plots for Shot 1 and Shot 2, respectively. Since the wired system was configured to record the seismic events during an impact ‘trigger’, the signals corresponding to the seismic event occur very close to time 0.

Using cross-correlation, we calculated the time lag between the signals with respect to the reference signal (Channel 1) and present results in Figure 4.11. The time lags for both the shots are zero, which indicates that the signals are perfectly time synchronized.

Figure 4.10: Signal plots for Shot 1 (left) and Shot 2 (right) from the wired Geometric-Geode system.
Next we evaluated the accuracy of the wired system by calculating the NRMSE of signal 2, 3, and 4 with respect to the reference signal. Figure 4.12 shows the box plot of the NRMSE calculated for each signal, with respect to the reference signal from Shot 1 (left) and Shot 2 (right). The red line is the median, the blue box represents the 25\textsuperscript{th} and the 75\textsuperscript{th} percentiles, and the ‘whiskers’ correspond to 2.7\sigma (where \sigma is the standard deviation); as shown there are no outliers. The median NRMSE is below 3%, which indicates that the wired Geometric Geode system has very good accuracy. We note that the median NRMSE is approximately 5% for Shot 1 and approximately 10% for Shot 7 for the wireless GeoMote WSN (i.e., with similar shot distances, see Figure 4.6).

To evaluate the precision we calculated the signal differences for all the unique combinations of signals for a given shot. Figure 4.13 represents the box plot with the NRMSE of signal differences calculated for Shot 1 (left) and Shot 2 (right). The red line is the median, the blue box represents the 25\textsuperscript{th} and the 75\textsuperscript{th} percentiles, and the ‘whiskers’ correspond to
Figure 4.12: Box plot showing the accuracy NRMSE between signals for Shot 1 (left) and Shot 2 (right) from the wired Geometric-Geode system.

2.7σ (where σ is the standard deviation), and the red points are the outliers. The median NRMSE is below 4% for Shot 1 and below 7% for Shot 2, which indicates that the wired Geometric-Geode system has good precision. We note the median NRMSE is approximately 5% for Shot 1 and approximately 9% for Shot 7 for the wireless GeoMote WSN (i.e., with similar shot distances, see Figure 4.7).

Lastly, we plot the power spectrum for Shot 1 and Shot 2 to visualize the frequency components associated with the shots. Figure 4.14 and Figure 4.15 show the power spectrum for Shots 1 and 2, respectively. From the power spectrum plots we infer that the seismic events (sledge hammer impacts) occur very close to time zero, which can be confirmed by the time domain plot from Figure 4.10 for Shot 1 (left) and Shot 2 (right), respectively. We also note the maximum power associated with the signals were during the initial 0.4 seconds of the signal, as indicated by the red colored section in the power spectrum from Figure 4.14 and Figure 4.15.
Figure 4.13: Box plot showing precision NRMSE of signal differences for Shot 1 (left) and Shot 2 (right) from the wired Geometric-Geode system.

Figure 4.14: Power spectrum for Shot 1 from the wired Geometric-Geode system.
Figure 4.15: Power spectrum for Shot 2 from the wired Geometric-Geode system.

4.3 Conclusions

The results presented in this chapter indicate that our low cost Arduino-based GeoMotes perform comparably in terms of accuracy and precision. From the evaluations of longer shot data (e.g., Shot 7 for GeoMote WSN and Shot 2 for Geometric-Geode), we infer that distance affects the precision of both the systems. We hypothesize that the reduction in accuracy and precision at longer shot distances are due to the noise associated with the signals. This noise reduces the signal quality and increases the errors.

The time domain and frequency spectrum analysis indicates that the motes are capable of performing well at higher distances (such as 100 feet). With an efficient time synchronization protocol, we believe that the GeoMote-based system can be considered as a research grade wireless sensing tool. The system is inexpensive, adaptable to various conditions and easily deployed.
CHAPTER 5
RESULTS AND FINDINGS FROM LINEAR ARRAY EXPERIMENT

In this chapter we share our findings from the Linear Array Experiment we conducted to evaluate the GeoMote WSN. The Linear Array Experiment, commonly referred to as a ‘Seismic Refraction Tomography Survey,’ can be used to evaluate the capability of a system for full scale deployment of a refraction survey. Compressional waves, or seismic P-waves, are one type of seismic wave that is generated from an impactive source, such as the sledge hammer blow used in this experiment. P-waves generally exhibit the fastest wave propagation velocity of all types of seismic waves, and thus are the first energy to reach sensors at some distance from the source point.

Using the data collected from both the wired and the wireless systems, we manually picked the first arrival time of the P-wave energy at each geophone sensor location. We then used these arrival times to perform velocity calculations (tomographic inverse modeling) and construct 2D cross-sectional models of the determined seismic velocity. These models represent the “best guess” of the seismic velocity distribution/structure in the subsurface directly below the linear array. We also used data collected from this experiment to calculate the signal accuracy of the wireless system compared to the wired Geometric-Geode system.

This chapter is organized as follows: First, we discuss the signal processing that we performed to prepare the data for analysis. Second, we present the findings from our T0 picks for a subset of the sample shots. Third, we provide the results of our velocity calculations from both systems and compare the accuracy of these results. Fourth, we present the results of our accuracy analysis between the wired Geometric-Geode and our GeoMote WSN. Lastly, we conclude this chapter with a summary of the results from our Linear Array experiment.

The first shot was at one end of the sensor array, the second shot was approximately at the center of the sensor array, and the third shot was at the other end of the sensor
Table 5.1: Shot distances and the channel of origin.

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Distance from the first geophone sensor</th>
<th>Channel of origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 Feet</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>80 Feet</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>170 Feet</td>
<td>18</td>
</tr>
</tbody>
</table>

array. Table 5.1 indicates each shot number and the distance of that shot in the linear array with respect to the first geophone sensor. The channel of origin represents the geophone at which the shot was delivered to create a seismic event. Our experiment provides a visual representation of the P-wave propagation across the subsurface covered by the sensor array.

Next, we provide the number of samples received from each sensor mote for the demonstrated shots. Table 5.2 provides the data samples that were received at the base station for Shot 1, Shot 5, and Shot 10. We observe that 5505 samples constitute the complete data for a given shot, but there are channels for which the received data is less than the expected 5505 samples. We note that this inconsistency in the data reception affected the tomography modeling, and reduced the accuracy of the predicted model.

### 5.1 Signal Processing

We followed similar steps for signal processing as done in our WalkAway experiment in order to prepare the linear array data for analysis. The GeoMotes were configured to a sampling frequency of 505 Hz. We reiterate that this non-standard sampling frequency is caused due to the integer division of the ADC’s voltage oscillator rates [4]. Since the wired system was configured to sample the data at 500 Hz, we resampled the data from the WSN at 500 Hz in order to create a common frequency for signal comparison and data analysis.

We analyze the signals captured by all the motes in the WSN and explain the process of picking the time zero (T0) for a given shot. For visualizing and analyzing the propagation of the P-wave across the subsurface, it is important to find the following entities with respect to each shot. First, we need to identify the channel of origin to understand where the shot
Table 5.2: Number of samples received for each shot.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Shot 1</th>
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<th>Shot 10</th>
</tr>
</thead>
<tbody>
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<tr>
<td>14</td>
<td>5492</td>
<td>5505</td>
<td>5505</td>
</tr>
<tr>
<td>15</td>
<td>5505</td>
<td>5505</td>
<td>5505</td>
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<tr>
<td>16</td>
<td>5505</td>
<td>5505</td>
<td>5493</td>
</tr>
<tr>
<td>17</td>
<td>4193</td>
<td>4225</td>
<td>4319</td>
</tr>
<tr>
<td>18</td>
<td>4704</td>
<td>5253</td>
<td>5505</td>
</tr>
</tbody>
</table>
Figure 5.1: Signal plot for Shot 1 (location marked with a green asterisk) showing all channels for the wired Geometric-Geode (black) and wireless GeoMote WSN (red).
Figure 5.2: Signal plot for Shot 5 (location marked with a green asterisk) showing all channels for the wired Geometric-Geode (black) and wireless GeoMote WSN (red).
Figure 5.3: Signal plot for Shot 10 (location marked with a green asterisk) showing all channels for the wired Geometric-Geode (black) and wireless GeoMote WSN (red).
was delivered, i.e., the origin for the P-wave (marked with a green asterisk in all the signal plots in this chapter). Second, since the wave originates near a given geophone, the time at which the seismic event is recorded by this geophone is considered to be time zero (T0) for the P-wave.

Once the T0 for a given shot is chosen, we then align other signals with the same amount of lag T0, so that all channels have a common relative time with respect to T0. This process of picking T0 is necessary in WSNs, because the wired and wireless systems do not have a common clock. Thus, the process of picking T0 aligns the signals from a given channel (for both the Geometric-Geode system and the GeoMote WSN) to a common time for comparing the signals and analyzing the seismic events.

Figure 5.1 shows the signals from the 18 channels, as captured by the Geometric-Geode system (plotted in black) and the GeoMote WSN (plotted in red) for Shot 1. The shot was delivered at one end of the linear array. The channel of origin for this shot was Channel 1 (marked with a green asterisk). We note that both the wired and wireless systems recorded a second seismic event (see Figure 5.1). We believe that this second event might have been the sledge hammer being dropped on the ground; thus, we ignore this second event in our analysis. Figure 5.1 shows the signal-to-noise ratio decreases as the distance from the shot increases beyond 110 feet, which can be visually observed in the data collected from Channel 12 to 18 for this shot. We, also note that the motes are not synchronized in the WSN.

Figure 5.2 shows the signals from the 18 channels, as captured by the Geometric-Geode system (plotted in black) and the GeoMote WSN (plotted in red) for Shot 5. The shot was delivered approximately in the middle of the linear array, at a distance of 80 feet from the first geophone in the array. The channel of origin for this shot was Channel 9 (marked with a green asterisk). Since the distance to the other geophones on either side of where the shot occurred was less than 110 feet, the signal-to-noise ratio for all the signals is relatively good. The wired data results in Figure 5.2 show that the P-wave was generated at Channel 9 and reached the other geophones in the array after some time.
Figure 5.3 shows all the signals from the 18 channels, as captured by the Geometric-Geode system (plotted in black) and the GeoMote WSN (plotted in red) for Shot 10. The shot was delivered at the opposite end of the linear array, with a distance of 170 feet from the first geophone sensor. The channel of origin for this shot was Channel 18 (marked with a green asterisk). We observe the same trend as we saw in Figure 5.1, with respect to the signal-to-noise ratio, but in reverse order, i.e., the channels that are at a distance greater than 120 feet (Channel 1 to 8) from Channel 18 have a higher level of noise associated with the sampled data.

5.2 Picking T0

In this section, we present our findings after (1) picking T0 for Shots 1, 5, and 10 and (2) aligning the wireless data with the wired data. The T0 picks were done manually by selecting the coordinates at which the first rising edge was recorded for the seismic event for the selected channel of origin. This channel of origin was 1, 9, and 18 for Shot 1, 5, and 10, respectively.

We note that there was a large time difference between some of the motes; thus, the seismic event was recorded prior to T0 in some cases. Thus, picking T0 and realigning the signals led us to classify the signals into two categories. The first category of signals, which we call ‘good’, are the ones that align well with respect to the wired system. For some signals, however, the realignment pushes the seismic event to a time frame that is prior to T0. Thus, the second category of signals results in the loss of relevant data and renders the channel as ‘bad’.

In Figure 5.4, we plot the signals from Shot 1 after the T0 pick and realignment. The channel of origin (Channel 1) is marked with a green asterisk. The black colored signals represent the data from the Geometric-Geode system and the green colored signals represent the data from the GeoMote WSN. The signal comparison indicates that there is a minimal compression of the wireless signals due to the difference in sampling rate in the two systems. Hence, we resampled the wireless data at 500 Hz and the resulting signals are plotted in
Figure 5.4: Signal plots for Shot 1 (location marked as green asterisk), after picking T0 and aligning the wireless signals (green - without resampling, red - with resampling) with respect to the wired system (black). Bad channels are boxed with blue dots.
Figure 5.5: Signal plots for Shot 5 (location marked as green asterisk), after picking T0 and aligning the wireless signals (green - without resampling, red - with resampling) with respect to the wired system (black). Bad channels are boxed with blue dots.
Figure 5.6: Signal plots for Shot 10 (location marked as green asterisk), after picking T0 and aligning the wireless signals (green - without resampling, red - with resampling) with respect to the wired system (black). Bad channels are boxed with blue dots.
red in Figure 5.4. We observe that, after resampling the wireless data, the wireless signals match the wired signals in several cases.

Figure 5.4 shows that Channels 4, 7, 8, 9, 11, 17, and 18 (i.e., channels boxed with blue dots) do not have red colored signals for the seismic event. We classified these channels as ‘bad’ channels (i.e., the signal after realignment occurs prior to T0) and, thus, do not consider them in our analysis.

Figure 5.5 shows the signals from Shot 5 after the T0 pick and realignment; in this case the channel of origin was nine. Red colored signals in Figure 5.5 are the wireless data after resampling at 500 Hz. We note that several channels in both Figure 5.5 and Figure 5.6 are marked as ‘bad’ channels (e.g., Channel 17). This result indicates that accurate time synchronization is very critical for geophysical sensing, without which the data analysis cannot be conducted effectively. We observe that, after the realignment, only Channels 2, 3, 6, 12, 13, 14, 15, and 16 from Shot 5 are usable in our future analysis.

We see a similar result for Shot 10, where the channel of origin was Channel 18. After the T0 pick and realignment, we note that good channels from Shot 10 are 1, 2, 3, 6, 10, 12, 13, 14, 15, 16, and 18 in Figure 5.6. Table 5.3 summarizes the categorization of signals after T0 pick and realignment for each shot presented.

In general, from Figures 5.4-5.6, we infer that the resampled signals from the wireless GeoMote WSN fit the wired Geometric-Geode system well in several cases. We also note the variable sample interval that results in a slight mis-alignment between the wired and wireless signals at certain time intervals (e.g., Channel 16 from Shot 1, Channel 15 from Shot 2, etc).

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Good channels</th>
<th>Bad channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2,3,5,6,10,12,13,14,15,16</td>
<td>4,7,8,9,11,17,18</td>
</tr>
<tr>
<td>5</td>
<td>2,3,6,12,13,14,15,16</td>
<td>1,4,5,7,8,9,10,11,17,18</td>
</tr>
<tr>
<td>10</td>
<td>1,2,3,6,10,12,13,14,15,16,18</td>
<td>4,5,7,8,9,11,17</td>
</tr>
</tbody>
</table>

Table 5.3: Good and bad channels for each shot.
Figure 5.7: Signal plots for Shot 1 (location marked with a green asterisk), after picking T0 and aligning the wireless signals (left plot). In the right plot (zoomed), the wireless data is time-aligned but without resampling (in green) and time-aligned with resampling (in red). In both plots, the wireless data is plotted with respect to the wired data (black). Bad channels are boxed with blue dots.
Figure 5.8: Signal plots for Shot 5 (location marked with a green asterisk), after picking T0 and aligning the wireless signals (left plot). In the right plot (zoomed), the wireless data is time-aligned but without resampling (in green) and time-aligned with resampling (in red). In both plots, the wireless data is plotted with respect to the wired data (black). Bad channels are boxed with blue dots.
Figure 5.9: Signal plots for Shot 10 (location marked with a green asterisk), after picking T0 and aligning the wireless signals (left plot). In the right plot (zoomed), the wireless data is time-aligned but without resampling (in green) and time-aligned with resampling (in red). In both plots, the wireless data is plotted with respect to the wired data (black). Bad channels are boxed with blue dots.
We illustrate our conclusions from Figures 5.4-5.6 with another set of plots that further demonstrate the results of our realignment. The plots on the left, in Figures 5.7-5.9, show the data from the wired Geometric-Geode system (black) and GeoMote WSN (red with resampling and green without resampling). We observe from the plots on the left that seismic events are not aligned correctly for bad channels. In the plots on the right, the wireless data that has been time-aligned is plotted in green (without resampling) and the same signals resampled at 500 Hz are plotted in red. These findings indicate that, although the GeoMote WSN was successful in capturing the seismic events for a given shot, the captured data could not be used for refraction analysis due to the lack of time synchronization. In short, an accurate time synchronization mechanism is mandatory for a wireless geophysical sensing system.

### 5.3 Arrival Time Analysis

A key aspect of seismic data analysis involves finding the arrival times of the seismic pressure wave at a given geophone (collected by a sensor node in the case of a wireless network). Arrival time analysis is essential for calculating the inversions and visualizing the earth’s subsurface. We calculated the arrival time for all the shots, but considered only the ‘good’ channels for that shot. Fortunately we were able to use a significant amount of data collected from all shots. There were originally 198 unique source-receiver pairs; 95 of these pairs were usable for tomography analysis, which corresponds to 48% of the GeoMote WSN’s data. To ensure fairness in comparison of tomography results, only the same subset of unique source-receiver pairs in the ‘good’ wireless data were used to perform the wired system’s tomography analysis.

To find the variance between the wired and wireless systems, we use the root mean square difference (RMSD) between each pair of data points. RMSD is calculated using:

\[
RMSD = \sqrt{(w_{sr} - g_{sr})^2},
\]  

\(5.1\)
Figure 5.10: Arrival times for the 95 Source-Receiver pairs in the Linear Array experiment. Arrival times from the wired system are plotted in black and from the wireless system are plotted in red.
where \( w_{sr} \) is the arrival time estimated for event \( s \) and receiver \( r \) in the wired system and \( g_{sr} \) is the arrival time estimated for event \( s \) and receiver \( r \) in the wireless system. A given geophysical WSN should generally have an RMSD of less than 1 ms. An RMSD less than 1 ms is a reasonable time synchronization precision to ensure recovery of detailed and subtle velocity structures of interest. In this study, however, the sample interval of the wireless GeoMote WSN was limited to no less than 2 ms, so an RMSD of less than 5 ms would be the hypothetical best-case time resolution of the data sets presented herein.

Figure 5.11: RMSD of arrival times between wired and wireless systems for Shot 1 (a), Shot 5 (b), Shot 10 (c), and for all Shots (d).

Figure 5.10 presents the arrival times of all 95 source-receiver pairs plotted at various shot distances. Red and black points represent the arrival times for the wireless and wired system, respectively. The overlapping points in the plot represent the arrival time values that match between the wired and wireless data. We then calculated the RMSD of the arrival times for all the shots between the wired and the wireless systems, which is presented in Figure 5.11. The red line is the median, the blue box represents the 25\textsuperscript{th} and the 75\textsuperscript{th}
percentiles, the ‘whiskers’ correspond to $2.7\sigma$ (where $\sigma$ is the standard deviation), and the red points are the outliers. We infer that the median error was 0 ms for Shot 1, and 2 ms for both Shot 5 and Shot 10. The most notable trend from our RMSD results, shown in Figure 5.11 (d), is that the median error for all the arrival times is 2 ms.

5.4 Seismic Velocity and Tomography Modeling

Seismic velocity can be used to correlate different geological structures and is an important metric for geophysicists. Using the arrival time estimated, we calculated the velocity of the seismic waves generated due to the shot impact. “The velocity models were constructed using the inversion process running up to ten iterations. The process of inversion is an iterative minimization problem that seeks a velocity model that ‘describes’ the observed travel time data collected in the field” [14].

Figure 5.12: RMS error data for the velocity models at each iteration. Error values are plotted in black and red for the wired and wireless systems, respectively.
The root mean square error plot from Figure 5.12 shows the recovered RMS values (i.e., the differences between the picked arrival times and the forward-modeled arrival times) for each iteration of the inverse modeling process. We observe that both the wired and wireless models start to converge at the fourth iteration of the inversion process. In other words, the RMS no longer decreases significantly beyond iteration four. We note that both models have approximately the same RMS value of approximately 10 ms at iteration four. “This indicates that the two models fit their associated data equally well, suggesting that this is a good iteration to compare the velocity models” [14].

Due to the result in Figure 5.12, our velocity model comparisons are based on the fourth iteration of the inversion process. Figure 5.13 and Figure 5.14 show the velocity models from the wired Geometric-Geode and wireless GeoMote WSN respectively. The receivers are plotted as green circles and the sources are plotted as red asterisks along the ground.
Figure 5.14: Velocity model recovered from the wireless data. This recovered velocity model should be very similar to the velocity model recovered from the wired system’s data with the same exact set of source-receiver pairs.
surface (at elevation zero in Figure 5.13 and Figure 5.14). Low velocities are plotted in blue and green, while fast velocities are plotted in red and yellow. We observe that there are some similarities between the two recovered models. That is, the recovered velocities are fairly similar in magnitude, and both the wired and wireless systems are able to recover the uppermost low velocities (see blue boxes). The initial increase in velocity (see green boxes) between 4 and 7 meters below the surface is also similar between the wired and wireless systems. We infer from the velocity models that the ground composition is soft soil up to a depth of four meters, as indicated by the slower velocities in Figure 5.14; as the surface depth increases beyond four meters, the ground composition transitions to harder soil.

![Velocity Differences (Wired-Wireless)](image)

Figure 5.15: Velocity differences between the velocity models recovered independently from the wired and wireless data.

Below a depth of seven meters, there are significant differences in the velocities of the two systems. This fact is shown by velocity differences in Figure 5.15. This result can be a major concern in the application of a GeoMote WSN in a real-world geophysical survey. We hypothesize that the differences in recovered velocities are due to the differences in the
arrival picks, and dictate the need for an accurate time synchronization mechanism to obtain an accurate tomography model.

### 5.5 Accuracy Analysis

To evaluate the accuracy of our WSN against the wired system, we calculated the normalized root mean square error (NRMSE) between the seismic event acquired by the wired and wireless systems. For each shot, we calculated the NRMSE between the seismic events recorded by wired sensor one and GeoMote sensor one, wired sensor two and GeoMote sensor two, etc. We assume that the wired data is the ground truth and estimated the error in the GeoMote WSN signal recorded with respect to the ground truth. We note that the NRMSE evaluations were completed for all good channels mentioned in Table 5.3.

Figure 5.16: Box plots showing NRMSE between the wired and wireless systems for Shot 1 (left), Shot 5 (middle), and Shot 10 (right) for all good channels.

Figure 5.16 shows the box plots of the NRMSE calculations for all the good channels from Shot 1, 5, and 10. The red line is the median, the blue box represents the 25th and
the 75th percentiles, the ‘whiskers’ correspond to $2.7\sigma$ (where $\sigma$ is the standard deviation), and the red points are the outliers. From Figure 5.16, we observe that the median error varies from 7.3% to 14.6%. We note that the maximum median NRMSE error was within 15% for all the shots recorded. We hypothesize that this range of variation is caused due to two reasons. First, the signal compression that exists in the data acquired by the GeoMote WSN adds to the error. Second, the noise associated with the channels contributed to the error; as we note the data from wired system has comparatively less noise.

5.6 Amplitude Analysis

![Amplitude spectrum of the wired system (left) and the wireless system (right) for Shot 1, Receiver 3, with an offset of 20 feet.](image)

To evaluate the frequency response of the GeoMote WSN, we performed an amplitude analysis and present our findings in this section. Using the data obtained after T0 picks, we selected a unique shot-receiver pair for Shot 1, 5, and 10. These receivers were Channel 3, 12, and 15 for Shot 1, 5, and 10, respectively. We selected the same shot-receiver pair for the wired Geometric-Geode system for comparison. Table 5.4 summarizes the shot-receiver
Figure 5.18: Amplitude spectrum of the wired system (left) and the wireless system (right) for Shot 5, Receiver 12, with an offset of 30 feet.

Figure 5.19: Amplitude spectrum of the wired system (left) and the wireless system (right) for Shot 10, Receiver 15, with an offset of 30 feet.
Figure 5.20: Amplitude difference between the wired and the wireless system for Shot 1, Receiver 3 with an offset of 20 feet.

Figure 5.21: Amplitude difference between the wired and the wireless system for Shot 5, Receiver 12 with an offset of 30 feet.
pairs we considered for our evaluation, along with the distance offset for each pair.

Table 5.4: Shot-receiver pairs for amplitude analysis.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Channel of origin</th>
<th>Receiver</th>
<th>Distance offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>20 feet</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>12</td>
<td>30 feet</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>15</td>
<td>30 feet</td>
</tr>
</tbody>
</table>

We calculated the amplitude spectrum for these shot-receiver pairs using the discrete Fourier transform. These results are presented in Figure 5.17, Figure 5.18, and Figure 5.19 respectively. The plot on the left represents the amplitude spectrum from the wired Geometric-Geode system and the plot on the right represents the amplitude spectrum from the wireless GeoMote WSN. We infer that the same seismic impact results in different amounts of energy recorded by the two systems. We next plot the residual amplitude between signals, by subtracting the amplitude spectrum of the wired GeoMetric-Geode data from the wireless...
GeoMote WSN data for all the shot-receiver pairs mentioned in Table 5.4. Figure 5.20, Figure 5.21, and Figure 5.22 show the results from the amplitude difference calculation for each of these shot-receiver pairs.

5.7 Passive Data Analysis

To evaluate the performance of the GeoMote WSN during passive data collection using the same linear array setup, we calculated the NRMSE between signals of the Geometric-Geode system and the GeoMote WSN system. We collected four samples and share our findings from evaluating two samples in this section. Figure 5.23 shows the box plot of the NRMSE results for samples one (left) and two (right). The red line is the median, the blue box represents the 25th and the 75th percentiles, the ‘whiskers’ correspond to $2.7\sigma$ (where $\sigma$ is the standard deviation), and the red points are the outliers.

![Box plots showing NRMSE calculated between the wired and wireless systems for Sample 1 (left) and Sample 2 (right).](image_url)

Figure 5.23: Box plots showing NRMSE calculated between the wired and wireless systems for Sample 1 (left) and Sample 2 (right).
The results in Figure 5.23 indicate that the median NRMSE values are approximately 13% and 5.2% for Sample 1 and Sample 2, respectively. We note that the general trend from evaluating all four samples is that the NRMSE varies between 5% and 30%. We hypothesize that this range of variation is caused due to two reasons. First; the primary reason for such high NRMSE values is due to the noise associated with the WSN. Second, the wired and wireless systems were triggered manually to start sampling the data, and hence did not have a common time zero to identify the start of sampling. Thus, we had to realign the GeoMote signals using cross-correlation. Since some of the samples did not have a hammer impact event, applying the lags predicted by cross-correlation resulted in discarding more than half of the original signals. Thus, performing NRMSE using the realigned signal with respect to the wired signal (which is unchanged) resulted in a higher NRMSE value.

5.8 Conclusions

From our comparison of the Geometric-Geode system and the GeoMote WSN system, we found that the GeoMote WSN performs comparably well in tomography modeling at depths of up to four meters. Unfortunately the accuracy of the model reduces below the depth of four meters. We hypothesize that this is due to the lack of synchronized time and temporal compression of signals (sampling skew). These issues need further investigation in the future.

From our accuracy analysis we note that the signal noise and sampling skew affects the accuracy of the wireless GeoMote WSN. The amplitude analysis indicate that the same seismic event results in different amounts of energy recorded by the two systems, though the frequency response of the wireless GeoMote system is approximately similar to the wired Geometric-Geode system. Passive data analysis indicates that without an efficient time synchronization algorithm to align the signals during data processing increases the error associated with the wireless GeoMote system compared to the wired Geometric-Geode system.
CHAPTER 6
CONCLUSIONS AND FUTURE WORK

To address the need for a high precision sensing device for geophysical applications our team developed a low cost Arduino Fio based hardware solution - the GeoMote WSN. Version 3 of the GeoMote, which we choose for our evaluation, consumes minimal power and was easy to deploy on the field compared to the wired Geometric-Geode system. As the sensor platform was based on Arduino, we were easily able to integrate the essential open source Serial Peripheral Interface (SPI) and ADC libraries needed for the peripherals, resulting in rapid prototyping of the platform.

Preliminary results from our WalkAway and Linear Array experiments give us an indication that the GeoMote WSN performs comparably with the Geometric-Geode system. In the following two sections, we conclude our evaluation of the GeoMote WSN by summarizing our findings and proposing possible next steps.

6.1 Conclusions

The results presented from the evaluation of the GeoMote WSN in the WalkAway experiment show that the GeoMote WSN performs comparably to the wired Geometric-Geode system. The evaluations of longer shot data reveals that both systems are susceptible to a loss in precision at longer shot distances. The findings from the Linear Array experiments show the importance of time synchronization for deciphering the order of occurrence of seismic events.

From the Linear Array experiment, we note that, although the GeoMote WSN was capable of effectively capturing the seismic events generated by the sledge hammer impact, the lack of time synchronization resulted in some data being unusable for our evaluation. We observe that there is a variable amount of signal compression that happens in the data collected by the WSN, and we hypothesize that this might be due to data loss occurring
during the radio communication, i.e., see the number of samples received from each GeoMote for different shots in Table 5.2 (Section 5.1).

Although the motes are capable of switching the gain settings dynamically during an experiment, we used a gain of 32 for both the WalkAway and Linear Array experiments. With a gain of 32, the noise level in the data increases as the seismic events occur beyond 110 feet. We hypothesize that this is due to the ADC being configured in bipolar mode [4], which limits the voltage sensitivity of the ADC. We believe that configuring the ADC in unipolar mode will increase the voltage range [4]. This, in-turn, would result in less noise and better sensitivity at distances greater than 110 feet. Lastly, a notable side-effect of setting higher gains was that the data from the sensor near where the shot was delivered, were clipped due to the input voltage saturation at the ADC.

6.2 Future work

There are many steps that can be pursued next. We outline these steps in the following sections.

6.2.1 Time synchronization

The results from our WalkAway and Linear Array experiments highlight the importance of accurate time synchronization in a geophysical sensing system. Since we did not account for the logical time synchronization maintained by the SHARP protocol in our experiments, a new experiment to evaluate the WSN with the SHARP time synchronization protocol is needed.

6.2.2 On-mote storage

With the current SRAM size of 32KB, we can record samples up to 16 seconds in high precision (24-bits per sample) when the sampling rate is 505 Hz. This reduces to eight and four seconds if the motes sample at frequencies of 1 and 2 KHz, respectively. To address this issue, we have added secondary storage via a SD card slot to the GeoMote platform. This
change should be evaluated in a future deployment of the GeoMote WSN, to understand its impact on the battery life of the motes.

6.2.3 Data transfer and radio range

We used ASCII mode of transmission for communication with the GeoMote WSN. In general, ASCII mode is expensive as it results in higher data rates. The binary mode of transmission is efficient and light-weight compared to ASCII mode, but resulted in collisions during data transmission between the motes. We tried a hybrid mechanism of the base station transmitting the commands in ASCII and the motes transmitting the data back in binary, but this also resulted in collisions during data transmission from the motes. Hence developing an efficient binary communication mechanism is a potential future step to improve data rates and communication accuracy. Lastly, to confirm the data loss that we observed during the field deployments, further evaluation of the radio communications could be performed to quantify the data loss.

6.2.4 Voltage drop-outs and anti-aliasing filter

We have observed that the readings contain voltage drop-outs during the field deployments, which affect the data collection at the base station. The base station will have to have additional intelligence to identify these drop-outs and correct for them, before displaying the signal for visual inspection and writing the data to a file. We hypothesize that this effect might be due to the bipolar mode configuration of the ADC, which results in large values when the voltage is beyond the ADC’s sensing range. This result warrants the need to perform further field tests of the motes configured in unipolar mode. Lastly, we believe adding an anti-aliasing filter to the current mote platform will increase the signal sampling accuracy and aid the experimenter to use aggressive gain values and increase the sensitivity of the motes.
6.2.5 System scalability

Since each sensor mote is independent and executes the command from the base station, any change to mote software or radio configuration parameters needs a manual upgrade on the motes. This fact hinders the scalability of the system when testing a large number of the motes in the lab and on the field. An automatic firmware update mechanism, such as firmware update over air (FOTA), can be considered as a potential future step to provide a single common upgrade mechanism for the entire WSN.

6.2.6 Gain settings and location awareness

A key experiment to evaluate is the gain response of the motes configured in unipolar mode, in order to understand the effects of different gain settings at various distances. Although our motes are equipped with a GPS unit, further software development is necessary to make the motes location-aware in a typical experimental setup. There are many benefits of making individual motes aware of the location they are deployed in. One key benefit would be that the location of the seismic event is known prior to its occurrence in a typical refraction tomography setup. Thus, if the motes are location-aware, they can automatically switch the gain setting depending on the distance from the shot, resulting in better data quality.
REFERENCES CITED


