Critical Design Parameters and Operating Conditions of Wireless Sensor Units for Structural Health Monitoring

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ABSTRACT

This study examines how various hardware design choices and operating conditions would affect the quality of the data in a wireless sensing environment. A series of experimental investigations are carried out using a laboratory shaking table instrumented with off-the-shelf MEMS accelerometers. A wireless unit is developed to interface with these wired analog accelerometers to enable wireless data transmission. To reduce the overall design variance and aid performance analysis, this wireless unit is built using an off-the-shelf microcontroller and radio development board. The anti-aliasing filter and Analog-to-Digital Converters (ADCs) are the only custom-designed components in the hardware. By varying critical hardware configurations including using analog accelerometers of different commercial brands, adopting ADCs with various resolutions, and using radios with different carrier frequencies, the impact of these design variables is assessed; after multiple shaking table tests are completed, the collected data is processed and the corresponding results compared. The sampling rate and the wireless transmission range are identified as the most critical operating conditions resulting in repeated tests to assess their impact on the global performance of a wireless monitoring system. In all of the cases tested, data is collected using wire-based data acquisition system to serve as a performance baseline for evaluation of the wireless data transmission performance. Based on this study, the challenges in the hardware design of wireless sensing units and the creation of data processing tasks are identified.

INTRODUCTION

Although it has been less than a decade since wireless sensing technology has been applied to structural health monitoring, more and more literature has recently emerged in this fertile cross-disciplinary research area. Successes have been achieved in the development of academic wireless sensing unit prototypes to which arbitrary analog sensors can be interfaced, data wirelessly transmitted in a decentralized sensor network [1-3],
and embedded processing performed using digital signal processing (DSP) cores [4]. In addition to academic efforts, stand-alone wireless sensors and sensor-networks have also been explored by the civil-engineering community [6-8].

When employing wireless communications, the reliability of the communication signal has been recognized as one of the most critical technical limitations regarding wireless communications [9]. The reliability of wireless communications can be challenged by noise, path losses, multi-path effects and physical interference. After years of active research, there exists a large body of literature that has been dedicated to this critical issue. For example, Frequency Hopping Spread Spectrum (FHSS) techniques have been provided as one possible solution in this regard [10,11].

In structural health monitoring, reliability of the damage detection methods adopted are an equally critical issue. For example, Casciati et al. [12] cite the noticeable loss of packets using Crossbow MICA motes in the streaming mode compared to traditionally tethered sensors. Kurata et al. [6] also report packet losses during their testing of the same wireless sensor platform (Crossbow MICA Mote). Furthermore, others have identified low analog-to-digital conversion (ADC) resolutions as the source of power low-frequency performance of MEMS accelerometers [7].

These interesting findings presented in previous studies have prompted this work. Structural health monitoring systems are only possible when the development of hardware and embedded software are integrated. It can be seen that a systematic study is desirable for better understanding how various hardware design issues (e.g., the selection of ADC resolution, among others) and operating conditions affect the performance of wireless sensing units and the results from system identification algorithms executed by the sensors. Taking such a step will bring the field closer to the development of a self-interrogating wireless sensing system that provides civil engineers with accurate data and data interpretations.

DESIGN OF A WIRELESS SENSING UNIT WITH PERFORMANCE MODULARITY

A wireless unit is developed in this study to enable the wireless transmission of sensor measurements generated upon four channels to which single-ended arbitrary analog sensors, each with outputs ranging from 0 to 5 V, are attached. An off-the-shelf microprocessor and radio development board are employed, while a custom-designed data acquisition board is used to accommodate different ADCs with 10-, 12- and 16-bit resolutions. The overall design of the proposed wireless sensing unit with performance modularity (different
ADC resolutions) is shown in Fig. 1. The objective of designing a custom wireless sensing unit is to permit the study of noise contamination in the sensor data at different stages during the flow of data through the wireless sensing system. Furthermore, the propagation of measurement noise into the system identification result using the data is also assessed. As summarized in Fig. 1, the study is exhaustive in varying various hardware components of the wireless sensing unit design. Two different analog MEMS accelerometers, three ADCs with different resolutions, and wireless radios operating on two distinct carrier frequencies are the variations considered. An overview of each hardware components as well as software design is given as follows:

**Analog Sensors:** Two commercially-available analog MEMS accelerometers, Analog Devices ADXL105EM-1 and Silicon Designs SD2012-005, with output signal ranges spanning from 0 to 5 V are employed at different times with the wireless sensing unit. These specific accelerometers and others within their product families have been widely studied in the literature as part of structural monitoring studies centered on wireless sensing technologies.

**ADC and LPF:** The first and the most critical stage when concerned with data quality is the analog-to-digital (ADC) conversion process. The ADC takes the analog signal from a sensor and converts it into a digital format which can be understood and processed by a microcontroller. In this study, ADCs with 10-, 12- and 16-bit resolutions from the same vendor (Texas Instruments) are selected. It should be noted that all three ADCs have the same serial communication protocol for interfacing to the host microcontroller. Due to similar interfacing requirements, these ADCs were soldered onto a specially fabricated printed circuit board (PCB), creating a flexible system where different data acquisition boards can be readily connected to the microcontroller. The ADC channel pins were also brought out to a connector for easy connection to any analog sensor. To avoid aliasing of response data in the vicinity of the Nyquist frequency, a 4-pole Butterworth low-pass anti-aliasing filter (LPF) is designed from simple analog electrical components to have a cutoff frequency of 35 Hz. It is recognized that a generically designed low-pass filter might distort measurements signals. Hence, the effect of the LPF on measurement data quality will be examined as a key part of the study.

**Microcontroller:** A Motorola 68HC11 microcontroller mounted to a compact development board is selected as the computing element of the wireless sensor design. Also mounted to the development board is 32 KB SRAM, 32KB EEPROM, access pins for the SPI port and a built-in RS232 transceiver with a DB9 connector. The small amount of memory effectively limits the number of the data points that can be stored and subsequently sent by the radio. Based on this hardware limitation, it is decided to cap the size of time-history data streams at 12001 points in all the preliminary single channel tests herein.

**Radio:** For this study, original equipment manufacturers (OEMs) radios are selected. Specifically, MaxStream radios that operate on the 900 MHz and 2.4 GHz frequency bands are chosen. Both radios implement frequency hopping spreading spectrum (FHSS) as their primary modulation technique thereby ensuring a high degree of reliability in the wireless channel. Since propagation and path losses have different characteristics at different frequencies, the choice of using two different radio bands provides the authors with the ability to thoroughly analyze the effect of the carrier frequency on the overall monitoring system performance.

**OPERATIONAL PARAMETERS OF THE WIRELESS SENSING UNITS**

The operational parameters of the wireless sensing units explicitly considered in this study are: 1) the ADC sampling rate, and 2) the wireless transmission range. In particular, two sampling rates are considered including 100 and 500 Hz. The lower sampling rate is typical in structural engineering applications, such as the recording of structural responses during seismic disturbances. In almost all wireless sensor systems, a main goal of their design is to achieve is a delicate balance between the maximum permissible transmission range and the lowest required electrical power requirements of the radio [10,11]. However, the issue is more complex for structural monitoring because the transmission range, i.e., the distance between the transmitting and receiving radio, must be sufficient to cover the large spatial dimensions of civil structures; insufficient range would clearly adversely impact the capabilities to capture the response of structures.

The major factor impairing the performance of a wireless communication system is signal attenuation. This phenomenon is caused by two factors: first, by the absorption of the radio's electromagnetic energy by the propagation medium, and, second by beam divergence which is the spreading of the radio signal as it travels away from the transmitting source. With respect to terminology, path loss refers to the reduction of radio energy as it propagates along a path, which is different from packet loss which refers to a receiver not receiving
a data packet. Many different propagation models are available that provide estimates for effects signal
distortion and path losses. Most often, these models combine empirical measurements with physics-based
propagation models to account for the different ways in which a radio signal travels (e.g. the Okumura-Hata
propagation model (see [10,11]) and the model in [13]). Since significant path loss and signal distortion will
ultimately result in packet losses, wireless propagation models can potentially provide guidelines for roughly
estimating the transmitting range, with respect to the occurrence of routine packet losses. Two situations
associated with the complex transmitting environment for structural health monitoring are considered in this
study:

Effect of Building Materials: Building materials affect the transmission of radio frequencies [14]. When
adopting wireless sensing for structural health monitoring, effective means for assuring the quality of data when
transmitted through building materials must be addressed.

Effect of Antenna Height: Placing an antenna at an elevated height has been widely applied as an effective
means for maximizing the transmission range of wireless communications [10,11]. To implement the idea of a
decentralized wireless sensor network for structural health monitoring, it may or may not always be possible to
extend an antenna to a satisfactory height.

EXPERIMENTAL INVESTIGATIONS

The experimental investigation is considered in two parts. In Part I, loopback tests are conducted using the
MaxStream radios. These tests examine the transmitting range of the radios and characterize the transmitting
environment. Based on the results of Part I, time histories of shaking table tests were collected at several
locations that result in different degrees of packet loss. At each location, various combinations of hardware
design options and operating conditions are studied.

All of the experiments are carried out inside and/or in the vicinity of the Fears Structural Engineering Laboratory
(abbreviated as Fears Lab herein) at the University of Oklahoma. The laboratory is located in an open terrain
landscape on the south campus of the university where the buildings are low-rise and sparse. The surrounding
areas have a slightly higher elevation than the lab. Around some of the buildings in the testing area, there are
a number of large trees. The tests reported herein are conducted spanning from late September to the end of
October when the fall started and most of the trees in the testing area had full leaves. This information is
specified here since the foliage condition has a great impact on wireless transmission especially in rural areas
[15]. Leaves can absorb radio waves, thus repeating the same test at the same location during the winter
should have better transmission than in the summer. Also the traffic was light during the day time when the
tests were conducted. All the tests were performed when there was little activity in the lab.

The building that houses the Fears Lab was constructed during the 1970’s. On its west side, there is one high
bay area with a strong floor, while an attached office area is on its east side. The high bay area is a steel
structure 24 feet high measured at the corners of the eastern and western edges. There is an 8-inch thick
masonry unit wall around the high bay area from the ground up until the height of 8 feet. Above that, there is a
0.025-inch thick steel sheet wall. An air-conditioned chamber is located inside the high bay area at the
southeast corner where the shaking table is bolted down to the strong floor. The chamber has the same
cement masonry unit wall that is 8-inch thick. The roof of the building is made of 2.5-inch thick timber
elements with a 10-inch insulation layer attached. All these building materials will affect the transmitting range
of the wireless connection.

This investigation offers a case study in which the focus is given to understanding how the data quality is
affected by a low antenna elevation and the need for the radio to transmit signals through building materials
common to typical university structural engineering laboratories. Throughout this study, the transmitting and
receiving radios were located at a fixed height of six feet above the ground. The 900 MHz Maxstream radio
was paired with a 1/4 wave monopole whip antenna, while the 2.4 GHz radio worked with a 1/2 wave dipole
antenna. A laptop is used on the receiver side to communicate with the transmitting wireless sensing unit.
Since the wireless sensing unit must remain mobile, it is powered by a simple 9V DC battery.

Loopback Tests: Given the complexity related to determining packet loss, experimental methods for
characterizing the transmitting environment and determining the transmitting range are needed. Loopback
tests are first adopted in this study to obtain the packet loss information for all the locations of the transmitting
wireless sensor and receiving laptop. Loopback tests were carried out at different laptop locations that
correspond to different transmission ranges while the wireless sensing unit is fixed at a location either inside or outside the Fears Lab. At each laptop location, the loopback test was repeated four times to obtain an average value of packet loss since radio frequency transmission is a stochastic process. For each test, the laptop radio transmits 100 packets, each 32 bytes in size, to the client wireless sensing unit radio, which in turn returns all the received packets to the server radio. The software operating at the server end counts all the good packets that it has received and displays the appropriate result.

Four sets of results were obtained from the loopback tests performed using the two different MaxStream radios with the wireless sensing unit client located inside and outside the lab, respectively. Fig. 2(a) displays both client side conditions. For the outdoor condition, the steel post was placed adjacent to the west gate of the high bay area, while for the indoor condition, the steel post was placed beside the shaking table, and the top of the post almost reached the ceiling of the chamber. In all tests, the heights of the client and server sides were fixed at six feet. Fig. 2(b) presents a typical view of the transmitting environment and foliage condition during the fall testing time. One set of the loopback test results is projected upon the map in Fig. 2(c) where the client side (shown by a red star) was indoor. Readings were taken along the four main directions (north, west, south and east) in the map. Multiple server locations where the loopback test was conducted are highlighted as orange dots with the average packet loss of four samples indicated. The locations and plane dimensions of all the buildings shown on the map are schematic.

**Preliminary Results of Shaking Table Tests:** In this study an electromagnetic shaking table was used to excite analog accelerometers attached to it, as shown previously in Fig. 1. An arbitrary wave form generator card from National Instrument is used to generate a repetitive swept sine excitation to drive the empty shaking table. The card has a digital-to-analog resolution of 12 bits. The swept-sine starts at 0.10 Hz and ends at 20 Hz with a duration of 15 seconds. All of the shaking table data is steady-state response. The data length is unified to be 12001 for all time histories collected as stated before. Such a data length permits the recording of one full run of the steady state response of the shaking table even at the 500 Hz sampling rate. The cases of using the analog sensors with a tethered data acquisition system (i.e., “wired” cases) are designed as the control experiment. In this test, sensor data is collected using a 16-bit NI DAQ card close to the location of the shaking table. The four “wired” cases include combinations of two types of accelerometers at two different
Tests are repeated under combinations of the various hardware options and different operating conditions. Three receiving laptop (server) locations are selected to measure packet losses and are numbered after the anticipated coverage rate as shown in Fig. 2. For example, location “100” is inside the chamber where the shaking table is located. The client (wireless sensing unit) and server (laptop) are under the same ceiling with a transmitting range of 16 feet, thus the anticipated coverage is 100%. Based on the results of the loopback tests with the same client location shown in Fig. 2, locations labeled as “90” and “80” are selected with the measured loopback coverage within the range of 90% to 100% and 80% to 90%, respectively. For each combination, three time histories were collected. When data is lost, the server inserts the artificial number of “0” in lieu of the true data point. Therefore a time history collected by the server can be readily converted into another one showing a blank spot for any data point lost in the wireless transmission so that the packet loss can be easily calculated. Some of the calculated packet losses using the collected time history samples at the three locations are presented in Table 1, where each 12001-point long sample was collected using the MaxStream 900 MHz radios. For brevity, only the results using the 16-bit ADC was presented. All the details of the hardware options and sampling rates are specified in Table 1, however this is for the clarity in presentation rather than showing the correlation between these factors and packet loss.

### Table 1. Measured packet loss during the shaking table tests when when the MaxStream 900 MHz radios are employed. Note that the packet losses during the loopback tests at Locations “80” and “90” are 2.00% and 13.5%, respectively.

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>With LPF</th>
<th>Sampling Rate</th>
<th>Location “100”</th>
<th>Location “90”</th>
<th>Location “80”</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL105EM-1</td>
<td>Yes</td>
<td>500 Hz</td>
<td>0.73%</td>
<td>12.87%</td>
<td>21.06%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>Yes</td>
<td>500 Hz</td>
<td>1.31%</td>
<td>7.87%</td>
<td>17.22%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>Yes</td>
<td>500 Hz</td>
<td>2.45%</td>
<td>17.97%</td>
<td>20.72%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>500 Hz</td>
<td>1.31%</td>
<td>9.28%</td>
<td>10.64%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>500 Hz</td>
<td>0.75%</td>
<td>5.62%</td>
<td>10.78%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>500 Hz</td>
<td>1.20%</td>
<td>4.82%</td>
<td>7.36%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>100 Hz</td>
<td>0.97%</td>
<td>11.41%</td>
<td>14.76%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>100 Hz</td>
<td>0.95%</td>
<td>9.77%</td>
<td>9.62%</td>
</tr>
<tr>
<td>ADXL105EM-1</td>
<td>No</td>
<td>100 Hz</td>
<td>1.15%</td>
<td>11.67%</td>
<td>6.42%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>Yes</td>
<td>500 Hz</td>
<td>0.66%</td>
<td>0.77%</td>
<td>19.25%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>Yes</td>
<td>500 Hz</td>
<td>0.66%</td>
<td>1.38%</td>
<td>17.56%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>Yes</td>
<td>500 Hz</td>
<td>1.48%</td>
<td>1.34%</td>
<td>25.61%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>No</td>
<td>500 Hz</td>
<td>0.65%</td>
<td>0.74%</td>
<td>10.27%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>No</td>
<td>500 Hz</td>
<td>1.29%</td>
<td>1.21%</td>
<td>27.48%</td>
</tr>
<tr>
<td>SD2012-005</td>
<td>No</td>
<td>500 Hz</td>
<td>1.25%</td>
<td>4.10%</td>
<td>13.44%</td>
</tr>
</tbody>
</table>

It can be seen from Table 1 that packet loss is quite common. Even a close distance of 16 feet (i.e., Location “100”) could cause packet loss using the current design. Packet loss can be considered as a random process, thus more realizations of this random process need to be collected to study if a loopback test can be used to characterize a transmitting environment and related to the packet loss in a real time history transmission although the loopback mode differs from the direct transmission mode.

Fig. 3 demonstrates how the transmitting range affects the completeness of the data set. These plots are the truncated time histories of 8000 points for the two cases framed by a broken line in Table 1 as well as their controlling “wired” case. The DC-offset caused by the LPF can also be observed by comparing the plots side by side, the adverse effect of which can be reduced in a refined design of the LPF. All of the “wireless” cases adopt an ADC of 16 bits while the “wired” case was collected using a 16-bit NI DAQ card. When the excitation is well-controlled in an indoor laboratory test, as in this study, and the sampling rate is reasonably high (100 Hz and 500 Hz), the results without using a LPF are not considered completely meaningless.

### DISCUSSIONS AND CONCLUSIONS

The above preliminary results from the experimental investigations have demonstrated the challenges in designing a wireless sensing unit. In particular, it clearly shows how critical the reliability of the wireless communication channel is when applying wireless sensing units over large spatial distances, as would be...
common in structural health monitoring. Packet losses caused by building materials and transmitting ranges must be reduced if data is to be used for detecting structural damage. Possible solutions may be 1) to raise the height of the antenna, however this needs further scrutiny especially for the nodes in a decentralized wireless sensor network, 2) to effectively increase the complexity of the software in the design of the wireless unit to re-transmit any lost data sets (as is common in sophisticated network protocols like TCP/IP). Nevertheless, this solution might not be suitable for a real-time health monitoring system that is required to deal with extreme and/or transient events. It shows clearly the necessity of developing smart wireless sensing techniques. If data were collected and processed onboard using an embedded system, the result to be transmitted would no longer necessarily be a sensitive raw time history, but rather some simplified indicators that alert building owners to the status of the monitored structure. Thus the adverse effect of packet loss can be reduced through local data interrogation.

Different from a cable-based monitoring system, the issue of missing data has to be addressed in a wireless sensor network. Numerical interpolation would be an effective means to restore the missing data points when packet loss is low as in the cases of Location “100”; however, a numerical interpolation becomes an extrapolation when the missing points are clustered (see Fig. 3 for the cases of Locations “90” and “80”). In that case, the trend line would be hard to capture especially for a nonstationary process and/or nonlinear response. Statistical approaches should also be exercised to fuse data [16] especially by condensing the “redundant” sets of data to achieve a data set with a reduced packet loss to enable further numerical interpolation. What has been investigated in this study is the case of applying a deterministic excitation to a deterministic system. How to handle more complicated situations remains a challenge that the authors will address in further study.

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