USGS/NEHRP External Research Earthquake Hazards Program
Final Project Report

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ABSTRACT

We report our findings from a funded project to develop and test a wireless, portable, strong-motion network of up to 40 accelerometers for structural health monitoring. The ultimate goal was to collect ambient vibrations for several days from USGS-instrumented structures. Structural health monitoring has important applications in fields like civil engineering and study of earthquakes. The emergence of wireless sensor networks provides a promising means to such applications. However, while most wireless sensor network s are still in the experimentation stage, very few take into consideration the realistic application requirements. To collect comprehensive data for structural health monitoring civil engineers, high-resolution vibration sensors and sufficient sampling rate should be adopted, which makes it challenging for current wireless sensor network technology in the following aspects: processing capabilities, storage limit, and communication bandwidth. The wireless sensor network has to meet expectations set by wired sensor devices prevalent in the structural health monitoring community. For this project we built and tested an application-realistic portable wireless sensor network called ShakeNet for instrumentation of large civil structures, especially for buildings or bridges after earthquakes. ShakeNet can be deployed by 2-3 people within hours after an earthquake in order to measure the structural response of the building or bridge using the aftershock data. ShakeNet involved the development of a new sensing platform (ShakeBox) running a software suite for networking, data collection and monitoring.

INTRODUCTION

Prior to this project period, we were already funded by NSF to purchase a total of 40 wireless portable seismometers (the ShakeBoxes) designed for temporary, aftershock-recording deployments. ShakeNet can be rapidly deployed on several floors of a large building or multiple locations on a large bridge with no dependence on existing power or communications infrastructure. It has been designed to collect structural vibration measurements for up to a week from each node within the network. This portable system can be used to instrument large structures within hours after an earthquake. Since there will be a need to deploy dense structural networks rapidly after a large earthquake has occurred, this network uses innovative hardware and software design to accommodate fast deployment by only one or two people. The network consists of two levels of complexity that make network reconfiguration based on suspected damage locations easier. The higher level nodes include a processor on which the algorithms would run continuously, reporting back to a central processing unit, e.g., the engineer's office computer (Master nodes). Lower, more primitive nodes consist of the sensor and digitizer (Motes), but these would be in constant communication with at least one higher level node. The results of the networking software could be used to redeploy nodes during aftershock sequences in areas where significant damage is suspected.

The network hardware consists of a low-power analog-to-digital conversion (ADC) board developed by Reftek. This board provides a 24-bit delta-sigma modulator at 200 samples/sec. Internally, the board uses a Cirrus Logic analog modulator, together with a digital filter. The sampling rate and filter coefficients are all programmable. This board interfaces with 3 Si-Flex 150 accelerometers from Colibrys Inc., and talks to a Crossbow Imote2 over the I2C bus. The accelerometers are among the most accurate and low-noise MEMS devices on the market. They provide full-scale ±3.5g measurements with a dynamic range of 120 dB. The Imote2 has an Intel processor, and several Mbs of RAM and flash memory. It uses an 802.15.4-compliant radio with a nominal data rate of 250 Kbps. The total power consumption of the unit is about 750 mW, lower than all other existing commercial Class A seismometers (from companies like Reftek and Kinemetrics). All ShakeNet hardware conforms to ANSS Class A strong-motion design specifications, the most accurate and advanced class of structural measurement systems (ANSS 2005, 2006).

ShakeNet was motivated by our work on instrumenting a long-span suspension bridge, the Vincent Thomas Bridge at the entrance to the Los Angeles Harbor, with wireless sensors. For the experiment twenty wireless sensors were deployed on the bridge, and the sensor network acquired vibration samples continuously from each sensor for 24 hours. Although the results from the experiment were encouraging in terms of quick deployment in a matter of hours, and the structural characteristics derived from the collected data being consistent with previously published results, a few shortcomings were highlighted. The MDA-400 vibration card with 16 bit ADC was used for capturing the vibrations was not suitable for capturing low (sub 1Hz) fundamental frequencies of large structures. As structure (e.g., buildings, bridges) sizes increase we wish to record lower fundamental frequencies associated with their natural frequencies of vibration, as they are of interest for structural analysis. In addition, the offsite development and preparation time required for the Vincent Thomas Bridge deployment was substantial.

Although we were able to extract macroscopic structural properties such as the modal frequencies, the specific board (the MDA-400 from Crossbow) that we used had several shortcomings. It has only 16-bit resolution; as we show below, this resolution is inadequate for monitoring ambient vibrations in large structures. It was originally designed for high-frequency sensing in the KHz range, so its response at the sub-1Hz modal frequencies of large structures is poor. It had a hardware fault which resulted in a signal offset that caused signal clipping at high amplitudes. Finally, the board was designed to interface only with a limited set of accelerometers, none of which was perfectly suited for structural sensing. A better accelerometer with higher signal to noise ratio and sensitivity is needed for structural health monitoring. We address these while developing ShakeBox for ShakeNet.

We were funded to test these new accelerometers to collect ambient vibration data and compute system identification of USGS-instrumented structures. The structures are of high research value in the civil engineering numerical modeling community because each contains an embedded, wired, strong-motion array, some of which have recorded large-amplitude ground shaking.

ShakeNet deployment requires placing the nodes in harsh radio environments. It requires the communication protocol to take care of packet drops and finding a route to the sink. Development of robust and working protocols for these operations from scratch requires considerable time and expertise. We do not envision the end users for ShakeNet to write wireless sensor network data collection and communication protocols. Use of an existing wireless sensor network software and modifying it for ShakeNets requirements would reduce the development time. We also needed a wireless sensor network which could be tasked to operate a number of applications. It needed to have tools which could help in rapid application development and changes to them as well as for rapid deployment in field. Tenet (Gnawali et al., 2006) fulfilled a number of these requirements and hence was used to develop the software suite required to run ShakeNet over the ShakeBoxes.

SYSTEM DESCRIPTION

ShakeBox description (hardware)

Figure 1. ShakeBox with weatherproof enclosure (left) and placement of detailed modules (middle), 6-inch ruler for scale: Right: a) CPU module with iMote2, b) power module, and c) A/D module.

In collaboration with Refraction Technologies Inc. of Dallas, we adopted a modular design paradigm for the ShakeBox (Figure 1, left and middle), which consists of four independent modules: CPU, Power, Analog to Digital (A/D) and Sensor, connected via standard SPI protocol. Figure 1 (right) shows the CPU, Power and A/D modules. These modules are housed in a custom-made weatherproof casing as shown in Figure 1 (left). Below is a short description of the different modules of ShakeBox and the associated characteristics.

CPU module

The CPU module contains the system processor (a Crossbow iMote2 mote) and the RT617 board and controls all system operations. The iMote2 mote controls the communication to other three modules via two SPI interfaces. The RT617 board consists of FPGA, precision oscillator, battery backed RTC, SD memory card slot, GPS interface and a board ID EEProms. It also provides the timing for the Power and A/D modules. IMote2 is an advanced sensor network platform and consists of a PXA271A 32bit microcontroller and CC2420 radio. It has multiple communication interfaces; prominent among those are the SPI, I2C, USB host and USB slave, JTAG and AC97 audio codec. CC2420 is an 802.15.4 compliant 2.4GHz radio which can give up to 256Kbps bit rate. Dynamic scaling of core frequency of the PAX271 microcontroller from 13MHz to 208MHz provides a varied range of options for balancing processing power with energy usage.

Power module

The Power module provides the power requirements of the different components and consists of RT618 FPGA board and RT620 power board. RT618 provides communication with CPU module, a clock, control of the voltage monitor A/D converter, control of analog power supplies and board ID EEProms. RT620 provides an input power controller, switching supplies at different voltage levels, a 16-bit A/D monitor for supply voltages and input currents, and a board ID EEProms.

Analog-to-digital module

The A/D module takes the analog sensor inputs and provides a time stamped 24 bit digital output and consists of RT618 FPGA board and RT614 analog board. RT618 provides communication with CPU module, a clock for time stamping sampling data, control of A/D chips, test-signal generator for debugging, relay control, a board ID EEProms and sensor ID interface. RT614 provides the scaling of sensor signal voltages, three 24-bit A/D converters, replays to connect test signals to internal analog inputs, a board ID EEProms and voltage regulators.

Sensing module

The sensor module consists of three Colibyrs SiFlex 1500 accelerometers, which are interfaced to the RT614 board in the A/D module. The SiFlex1500 operates from a bipolar power supply voltage that can range from ± 6V to ± 15V with a typical current consumption of 12mA at ± 6V. The linear full acceleration range is ± 3g with a corresponding sensitivity of 1.2V/g.

Weatherproof casing

The weatherproof casing houses all the modules. Each module is electronically shielded to protect against electromagnetic disturbance. The lead acid battery used in the ShakeBox is placed in a separate sealed compartment to isolate it from the electronics in case of battery leakage. The box provides serial connectors, connector for GPS, LEDs for display and feedback and antenna connector for high gain external antenna used by iMote2's radio. It has three screws and a spirit level for leveling. The prototype box in Figure 1 is made up resin plastic but the production pieces will be metallic aluminum.

Communication

Communication between modules in ShakeBox is achieved via three buses: the SEL bus, the SPI command and control bus, and the AD data bus. While the SEL bus is used by the iMote2 mote to select a specific component in a module, the SPI command and control bus (the SPI1 port on iMote2) is used to communicate with that component. The AD data bus (the SPI2 port on iMote2) is used for the iMote2 mote to collect sampling data from A/D module and auxiliary data from the Power module. During development we will need debugging facility and features to upload driver code and FPGA images on the boards. The board modules expose the JTAG port for FPGA programming while iMote2 is programmed and debugged using the USB slave port.

ShakeBox Description (Software)

The Tenet architecture

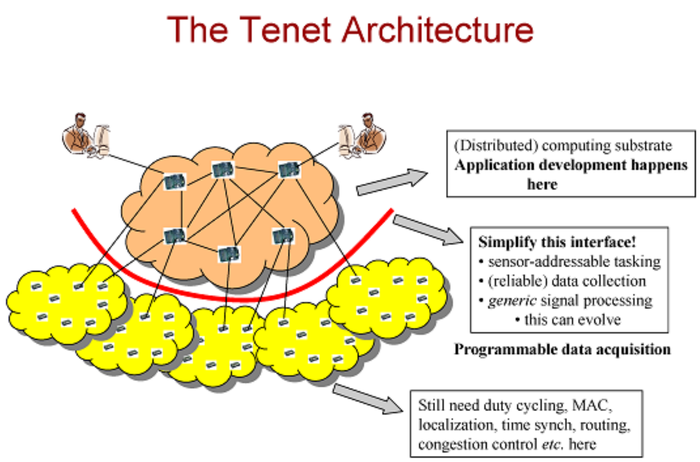

Figure 2. Schematic illustrating Tenet architecture: a lower tier consisting of motes and an upper tier consisting of masters.

The software for running ShakeNet has been built using the Tenet architecture. Tenet is based on the observation that for scalability, modern sensor network deployments have two tiers: a lower tier consisting of motes, which enable flexible deployment of dense instrumentation, and an upper tier containing fewer, relatively less-constrained 32-bit nodes with higher-bandwidth radios, which we call masters (Fig. 2). Tenet constrains the placement of application functionality in a sensor network according to the following Tenet Principle: Multi-node data fusion functionality and multi-node application logic should be implemented only in the master tier. The cost and complexity of implementing this functionality in a fully distributed fashion on motes outweighs the performance benefits of doing so. Since the computation and storage capabilities of masters are likely to be at least an order of magnitude higher than the motes at any point in the technology curve, masters are the more natural candidates for data fusion. The principle allows motes to process locally-generated sensor data, and can result in significant communication energy savings. Over the period of the project we were able to port the Tenet software suit for running over imote2 (the mote used for ShakeBox) and add additional features to be able to run ShakeNet.

The Driver

The communication protocol defines how each module should behave for information exchange. The driver implements such protocol according to the specifications. With the driver, the CPU module can turn on/off the power and sensor module and configure them respectively. The functionalities the driver can support include: 1) select a specified device on any of the modules; 2) read from and write to FPGA registers and EEProm on any of the modules; 3) collect sample data from the sensor and auxiliary data from power and A/D modules.

Steim and SDRAM support

ShakeNet data collection happens using the Tenet hierarchical architecture. We have a higher tier of master nodes which task the nodes and collect the data responses coming from them. However, the data collection capability is capped by the limited wireless radio bandwidth. To overcome this limitation, we implemented Steim's algorithm (SEED Reference Manual, 1993) for compressing data on each ShakeBox prior to sending it to the master. In addition, wireless links are well-known for the intermittent behavior (temporal link quality changes). To be able to better adapt under such conditions, we added the 32 MB SDRAM support at ShakeBox so that up to 14-hour data (at 100 Hz) can be buffered temporarily and then sent out whenever the link quality improves.

GPS Time Sync

Time synchronization is required for correlation of data collected across ShakeBoxes. Since ShakeBox will be placed inside a building or other structure with limited or no access to the open sky, using GPS for time synchronization will be challenging. We designed a novel way of achieving time sync. Before the deployment, we GPS time sync each ShakeBox and record the time offset of the CPU module. We repeat the same procedure after the deployment. With these two sets of offsets, we are able to compensate the clock drifts and adjust the timestamps for each ShakeBox accordingly.

LABORATORY TESTING/EXPERIMENTS

FFT and channel analysis with function generator

From May to June 2009, we conducted a series of experiments to test the accuracy of the ADC in the ShakeBox. The laboratory testing of the sensing hardware was to test the fidelity and integrity of the various components. The equipment we used was an HP33120A Function Generator, which accepts user parameters to generate an analog wave signal. We fed the input signal to the ShakeBox, collected the response from ADC and performed numerical analyses, such as FFT, coherence and cross-correlation between channels calculations. We varied the frequency range from 0.2~125Hz, which covers most frequencies of interest in earthquake engineering analysis, and the amplitude range from 1~19Vpp. We also measured the noise characteristics of each ADC channel, with and without function generator connected. The tests were conducted with and without the sensor, at 125, 250 and 500 sps. The tests were also conducted with battery and AC power. Tilt tests were conducted to measure 1g input response. Due to space limitation, we only present one set of results here: frequency sweep from 0.2 to 125 Hz with 1 Vpp amplitude.

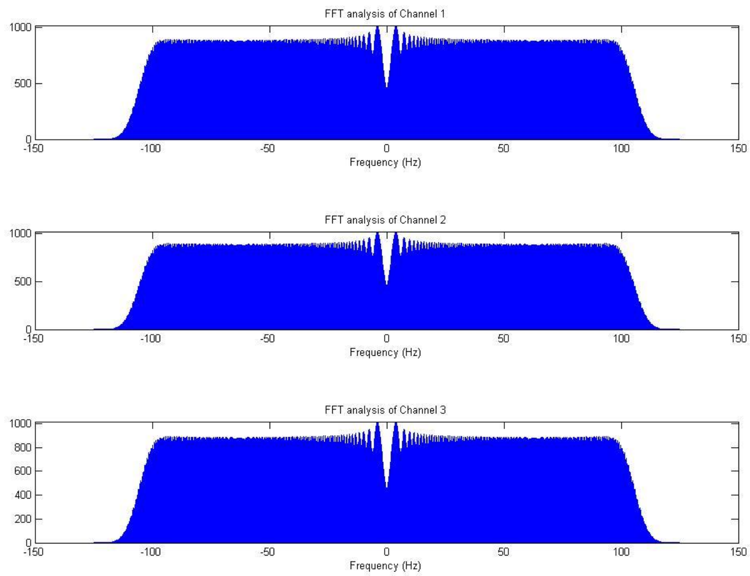

Figure 3. FFT analysis of input function generator frequency sweep 0.2-125 Hz with 1 Vpp amplitude.

Fig. 3 shows the FFT analysis for a frequency sweep from 0.2 to 125 Hz. It is readily apparent that the ADC has a reasonable response until around 100 Hz, and then the response drops dramatically from 100 to 125 Hz. This is expected behavior according to the ADC datasheet.

Shaketable test

In July 2009, we conducted the tests on a uniaxial shaketable at Caltech's Dynamics Lab in the Dept. of Mechanical and Civil Engineering. The goal was to test the accuracy of the ShakeBox Colibrys accelerometer (channel 2 and 3), by comparing its response with that of co-located Dytran piezoelectric accelerometer sensors (Fig. 4). A unidirectional electrodynamic shake table was used, and a sine wave at frequencies between 0.1 and 90 Hz was input into the table. The selected frequencies input frequencies were 0.1, 0.5, 0.8, 1, 1.2, 1.5, 2, 5, 10, 25, 45, 50, and 90 Hz. The response of the ShakeBox was compared with 9 piezoelectric accelerometers that had also been attached to the shaketable (Fig. 5). Halfway through the test the sensors were rotated to test orthogonal horizontal directions.

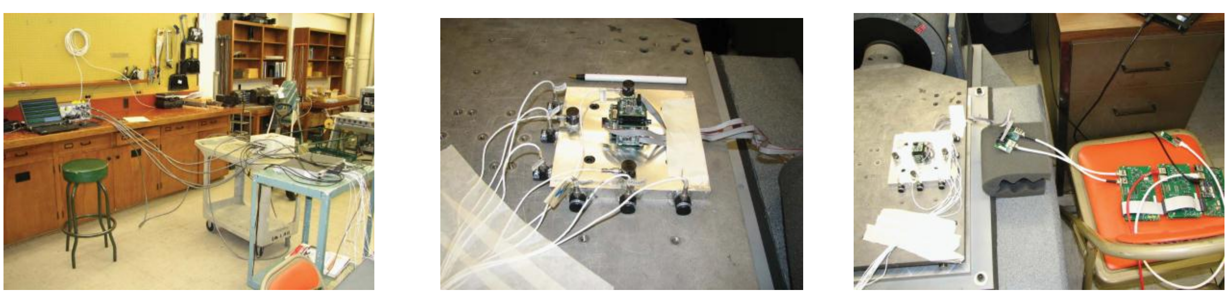

Figure 4. Uniaxial electrodynamic shaketable test setup showing dytarn accelerometer equipment (left), both the 9 Dytran accelerometers and ShakeBox Colibrys accelerometer setup on shaketable (middle), and the ShakeBox modules (right).

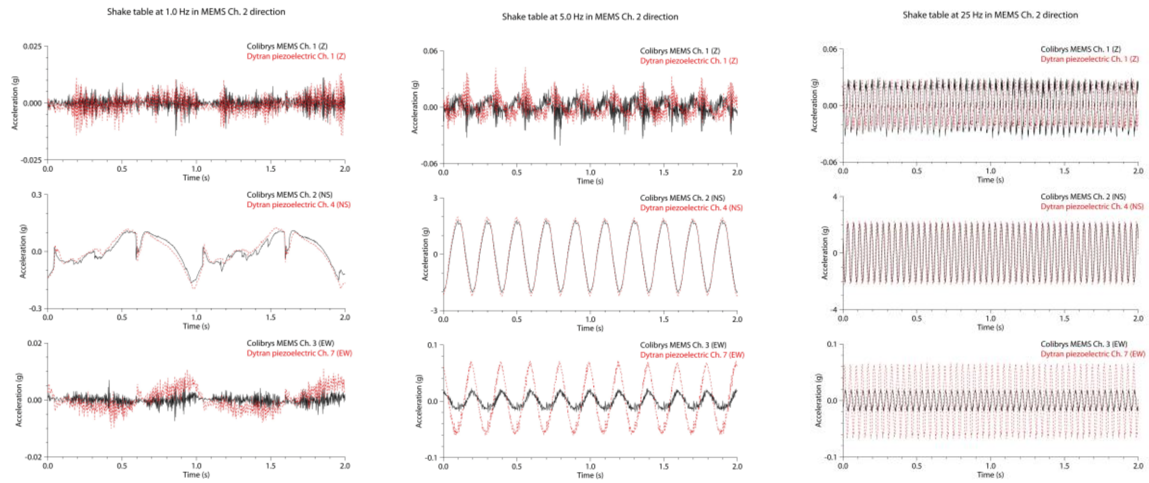

Figure 5. Uniaxial electrodynamic shaketable results comparing the ShakeBox response (black) with piezoelectric accelerometers (red). Sine wave input at 1 Hz (left – note that input is not a true sine wave due to shaketable limitations in this frequency range), 5 Hz (middle) and 25 Hz (right).

Shaking experiments in Millikan library

In October, 2009, we conducted a forced vibrations response experiment of two ShakeBoxes on the 9-floor of the 9-story reinforced concrete Millikan Library at Caltech. The objective of such experiment was to test the sensor precision and the working system as a whole. The building was shaken by a carefully controlled eccentric mass shaker on the roof at frequency sweeps in the north-south and east-west directions at 1.0 to 9.5 Hz. We deployed two ShakeBoxes: one on the basement level and one on the 9th floor, both within a few feet of a permanently installed 3-component Episensor-Q330 datalogger system. The comparison between our results and Episensors are shown in Fig. 6. The curves for the ShakeBoxes and Episensors show very good agreement at the response levels of the forced vibrations input, especially for the horizontal directions which recorded responses on the order of 0.1 and 10 mg. Note that the vertical direction was the only direction that differed somewhat between the two sensor types, possibly because these smaller amplitudes approached the internal noise levels of the MEMS accelerometer inside the ShakeBox.

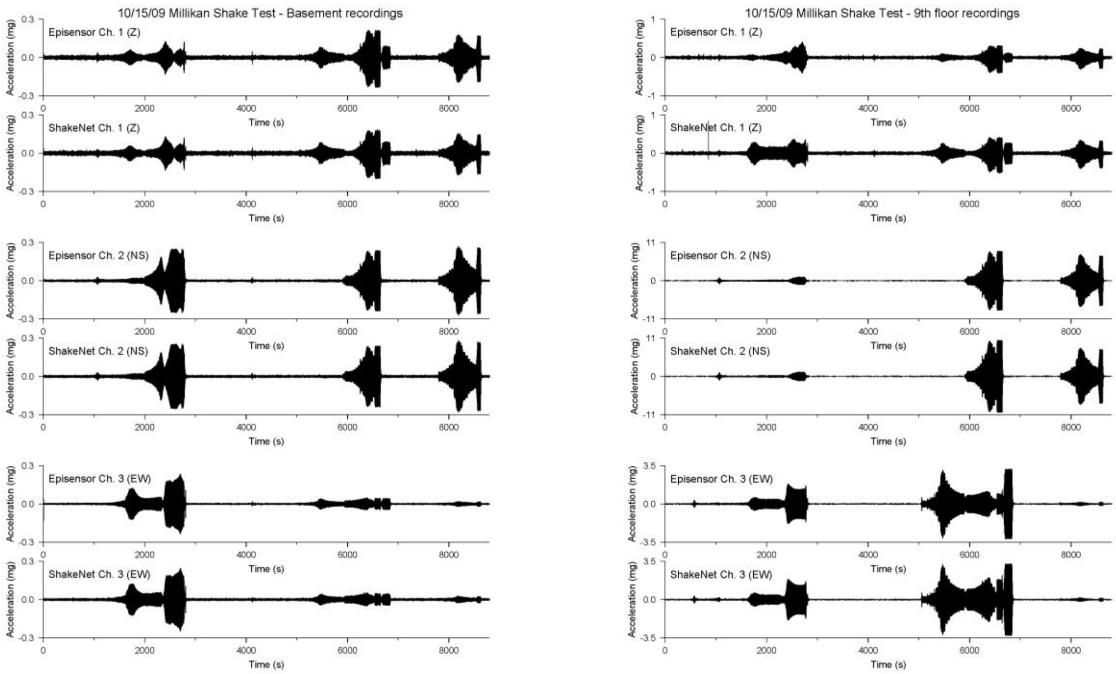

Figure 6. Millikan Library forced vibrations test. Comparison of 3-component ShakeNet records with co-located Episensor located on Basement (left) and 9th floor (right).

DEPLOYMENT EXPERIENCE

1100 Wilshire Blvd. building

In June 2011, we conducted our first ambient vibration deployment at the 1100 Wilshire Blvd. building. 1100 Wilshire Blvd. consists of a massive 15-story concrete cube that holds a 700-space parking structure. A 21-story steel moment-frame, triangular prismatic pentahedron sits on top of the cube (Fig. 7).

Figure 7. Photo and GoogleEarth SketchUp diagram of 1100 Wilshire Blvd. building in Los Angeles.

For three days, we operated 30 seismometers with 10 masters in the stairwells of several floors in the condo section of the building, as well as along outer walls on several floors of the garage. The network recorded ambient vibrations of the structure for the three-day time period. Since the seismometers used ultralow power 802.15.4 radios, they did not interfere with local Wi-Fi communications. The network configuration was as follows:

Level	#ShakeBoxes/masters
B3	3/1
B	3/1
1	2/0 (one for each stairwell)
2	2/2
3	2/0
16	2/0
17	2/2
18	2/0
20	2/0
21	2/2
22	2/0
36	2/0
37	2/2
38	2/0

Based on a pre-deployment site reconnaissance visit, we found that wireless communication was excellent in the open stairwells, likely because there is a significant amount of metal in the numerous handrails, as well as the stairs and inside the walls, providing a waveguide type of effect. Even for floors that were tall such as the lobby and conference room levels, communication from floor to floor within the stairwell was very good. Although we expected that we might need to use multihop, in nearly every case, placing the master in the middle of each cluster provided direct mote-master communication.

The primary weakness of this deployment, however, turned out to be the masters' hardware. Some were not as reliable as expected, and failed upon loss of communication. The eBoxes we used had several issues: 1) the operating system (Ubuntu 10.04) became unstable for some specific CPU frequencies and the OS would eventually hang for some of the eBoxes, 2) Not all USB ports functioned equally well. If the master mote was attached to a bad USB port, the data collection would stop half-way and the communication between the master and ShakeBoxes would be lost. On the other hand, throughout the 1100 Wilshire deployment, we were able to evaluate the integration test of the whole system, and tested the lifetimes of both ShakeBoxes and eBoxes powered by car batteries under realistic deployment conditions.

Fig. 8 shows spectra from a section of horizontal records from acceleration data. The spectra have been arranged in order of increasing height inside building with the bottom six spectra from within the parking garage cube. The more flexible steel frame triangular prismatic pentahedron produces peaks in the spectra that are more obvious to identify than the stiffer reinforced concrete cube. The upper stories show distinguishable peaks at 0.25 Hz (possibly the first translational mode), 0.4 Hz (first torsional mode), 0.7 Hz (second translational mode), 0.8 Hz, 0.9 Hz, 1.4 Hz, 1.6 Hz, 2.0 Hz and higher. The bottom six spectra show a slight peak at 2.15 Hz, possibly the first or second translational mode. The spectral lines in the spectrogram above 10 Hz are most likely due to machinery running at a range of frequencies and for limited time durations (e.g., HVAC, elevators).

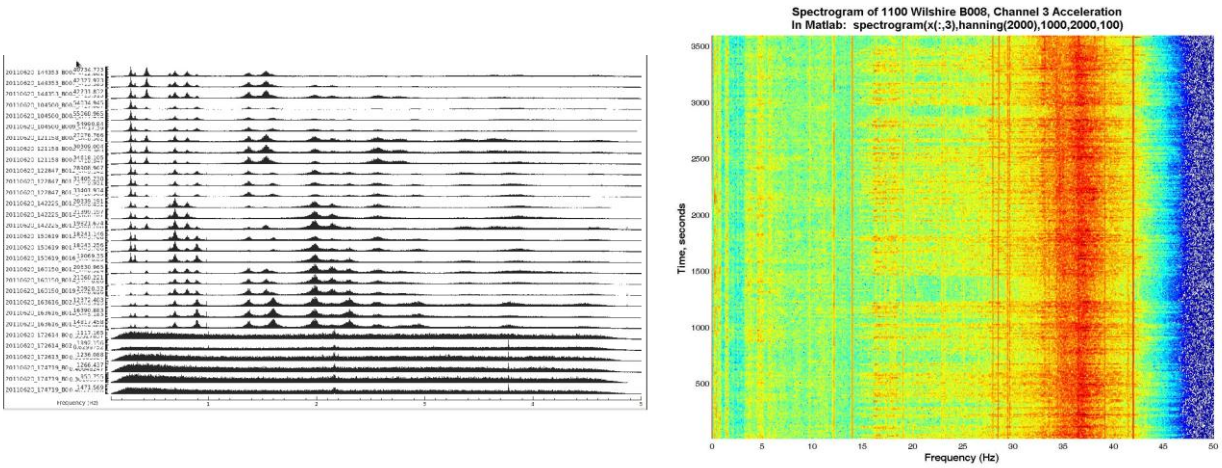

Figure 8. Left: Spectra from a one-hour section of waveforms from 30 ShakeBoxes deployed in the 1100 Wilshire Blvd. stairwells on various floors arranged from bottom of building to top. Right: Spectrogram from a section of horizontal component data recorded by a ShakeBox deployed on the 36th floor.

Seven Oaks Dam

In October 2011, we conducted our second deployment at the Seven Oaks Dam (Fig. 9). The Seven Oaks Dam sits within one km of the San Andreas fault and is located in a region of alluvial sediments in the southern foothills of the San Bernardino Mountains. It is a 550-ft-high by 2980-ft-long earth-and-rock-fill dam designed to provide flood protection to Orange County, California.

Figure 9. Seven Oaks Dam in Highland California. Right: network configuration showing locations (red squares) of a total of 31 seismometers.

For three days, we set up and operated seismometers in 31 locations along the Seven Oaks Dam crest road and the downstream switchback roads (see Figure 9, right). Specifically, we placed 24 seismometers at approximately 120-foot spacing along the crest road, 2 seismometers at 120-foot spacing along the center of all three downstream switchback roads, and 1 seismometer at the downstream base of the dam.

This deployment posed problems we did not anticipate, alerting us to issues that still needed to be solved before making ShakeNet fully reliable. We had expected that wireless communication would be excellent because of the clear mote-to-mote line of site and because there were no other WiFi signals present that would interfere with ours. Communication between some motes and masters was faulty, and we expect that more powerful antennas will partially solve this problem in the future. As with the previous deployment, the masters' hardware again posed problems for reliable data recording. During the data collection, we could not establish communication between the master and ShakeBoxes easily for at least four clusters. After trial and error placing of the antennas in various possible directions, we were able to reach all ShakeBoxes. But post-deployment analysis showed that the communication links did not last long before failing again. We hypothesize that the reasons for bad communication links might be that the antennas we used were relatively weak for outdoor environments (they worked well in the 1100 Wilshire deployment, which was indoor where walls helped reflect signals). Also the road surface was not flat and numerous small pebbles on the road may have helped scatter the radio signal. We also encountered a strange reset behavior in the USB driver of the master nodes. Due to the reliability issue of the previous master (ebox) nodes used at 1100 Wilshire, we replaced them with newer nodes with equivalent functionality and newer hardware (manufactured by Habey). The unpredictable resets occurred with three clusters and we need to further test these to pinpoint the root cause. It might be that these Habey nodes are faulty or that the master motes do not function well.

The very small ambient vibration amplitudes, near the internal noise level of the Colibrys sensors, precluded us from performing system identification from the three-day records.

The Santa Ana River Bridge

The Santa Ana River Bridge will be our final deployment later in winter, 2012 (Fig. 10). We had initially scheduled a deployment for November, 2011 but had to postpone the test due to software troubleshooting and minor hardware upgrades. The Santa Ana River Bridge, located 30 km from the San Andreas fault, supports a main water distribution feeder pipe for transporting Colorado River Aqueduct water to the rapidly growing communities east of Los Angeles. The bridge consists of three steel trusses supported by base-isolated piers in alluvial sediments over bedrock. Accelerometers from the wired array are located above and below the water feeder line, with several next to the base isolation units.

A reconnaissance visit to the bridge in November, 2011 with Metropolitan Water District of Southern California engineers allowed us to plan out the configuration of the three-day deployment, and to estimate likely wireless communication issues. We found a surprisingly large number of independent WiFi signals from local sources more than 100 feet from the bridge, but expect that we will get reliable communication and data recording from this test deployment.

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