SEI 06 Towards a multi-tier sensor array for instrumenting large buildings

SEI 06.1 Overview

Structural Health Monitoring (SHM) has important applications in fields like civil engineering and seismology. The emergence of wireless sensor networks (WSN) provides a promising means to such applications. However, while most WSNs are in the experimentation stage, very few take into consideration realistic application requirements. To collect comprehensive data for SHM domain experts, high-resolution vibration sensors and sufficient sampling rates should be adopted. This makes it challenging for current WSN 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. In this project, we are building an application-realistic portable wireless sensor network called ShakeNet for instrumentation of large civil structures, particularly buildings or bridges after earthquakes. ShakeNet will be easily deployable by 2-3 people within hours after an earthquake in order to measure the structural response of the building or bridge using aftershock recordings. ShakeNet involves the development of a state-of-the-art sensing platform (ShakeBox), and installation and execution of the Tenet software suite for networking, data collection and monitoring.

SEI 06.2 Approach

ShakeNet is 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. The results from the experiment were encouraging; deployments were done in a matter of hours, and the structural characteristics derived from the collected data were consistent with previously published results. However, a few shortcomings were highlighted; the MDA-400 vibration card with 16-bit ADC that was used for recording the vibrations was not suitable for capturing low (< 1Hz) fundamental frequencies of large structures. As the structure size increases we generally observe lower fundamental frequencies of vibration which are of interest for structural monitoring and analysis. In addition, the development and preparation time required off-site prior to deployment was substantial.

Although we were able to extract macroscopic structural properties such as the modal frequencies, the 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 in the sub-1Hz modal frequency range 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 was needed for structural health monitoring. We addressed these issues while developing the ShakeBox for ShakeNet.

ShakeNet deployment would have required placing the nodes in a harsh radio environment. 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 WSN data collection and communication protocols. Use of an existing WSN software and modification for ShakeNet requirements reduces the development time. We also need a WSN which can be tasked to operate a number of applications. It should also have tools which can help in rapid application development and changes to them, as well as for rapid deployment in field. Tenet fulfills a number of these requirements and hence has been used to develop the software suite required to run ShakeNet over ShakeBoxes.

SEI 06.3 System(s) Description and/or Experiments

ShakeBox Description

In collaboration with Refraction Technologies Inc. of Plano, TX, we are adopting a modular design paradigm for the ShakeBox (Figure 1, left), 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 then housed in a custom made weather-proof 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 the 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 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

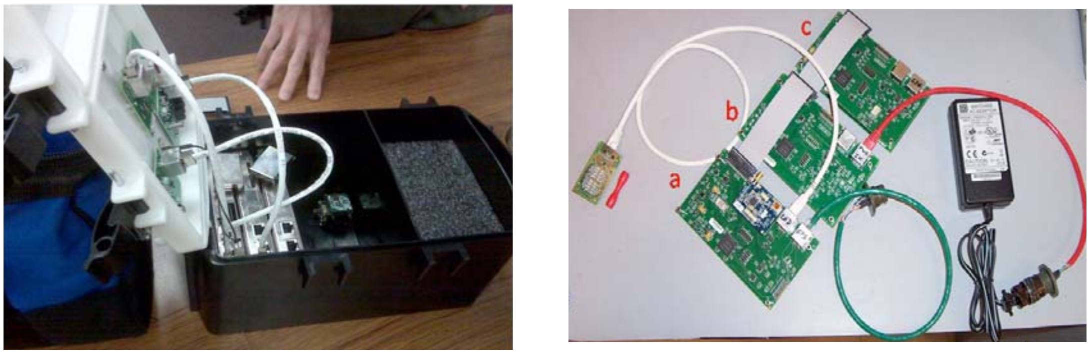

Figure 4. ShakeBox with weather-proof enclosure (left) and detailed modules (right):
a) CPU module with iMote2, b) power module, and c) A/D module.

interfaces; prominent among these 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 the 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.

Weather-proof 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, a connector for GPS, LEDs for display and feedback, and antenna connector for a high-gain external antenna used by the iMote2 radio. It has three screws and a spirit level for leveling. The prototype box in Figure 1 is made up of 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.

Tenet

The software for running ShakeNet has been built using the Tenet architecture. Tenet is based on the observation that for scalability, today's sensor network deployments ideally 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. 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 does allow motes to process locally-generated sensor data, and can result in significant communication energy savings. Over the period of the project we have been able to port the Tenet software suite for running over imote2 (the mote used for ShakeBox) and add additional features to be able to run ShakeNet.

Function generator test

From May to June 2009, we carried out a series of experiments to test the accuracy of the ADC in ShakeBox. The equipment we used was a HP33120A Function Generator which accepts user-defined parameters to generate an analog wave signal. We fed it to the ShakeBox, collected the response from the ADC and analyzed the resulting FFT, coherence, and cross-correlation between channels. We varied the frequency range from 0.2 to 125 Hz which covers significant frequencies in earthquake engineering analyses, and the amplitude ranged from 1 to 19 Vpp. We also measured the noise characteristics of each ADC channel, with and without function generator connected. Due to space limitation, we only present one set of results here: frequency sweep from 0.2 to 125 Hz with 1Vpp amplitude. For more details, please refer to http://enl.usc.edu/enlwiki/ShakeNetTestResultLatest.

Figure 2 shows the FFT analysis for a frequency sweep from 0.2 to 125 Hz. We can see that the ADC has a reasonable response until around 100 Hz, above which the response drops dramatically from 100 to 125 Hz. This is expected behavior according to the ADC datasheet.

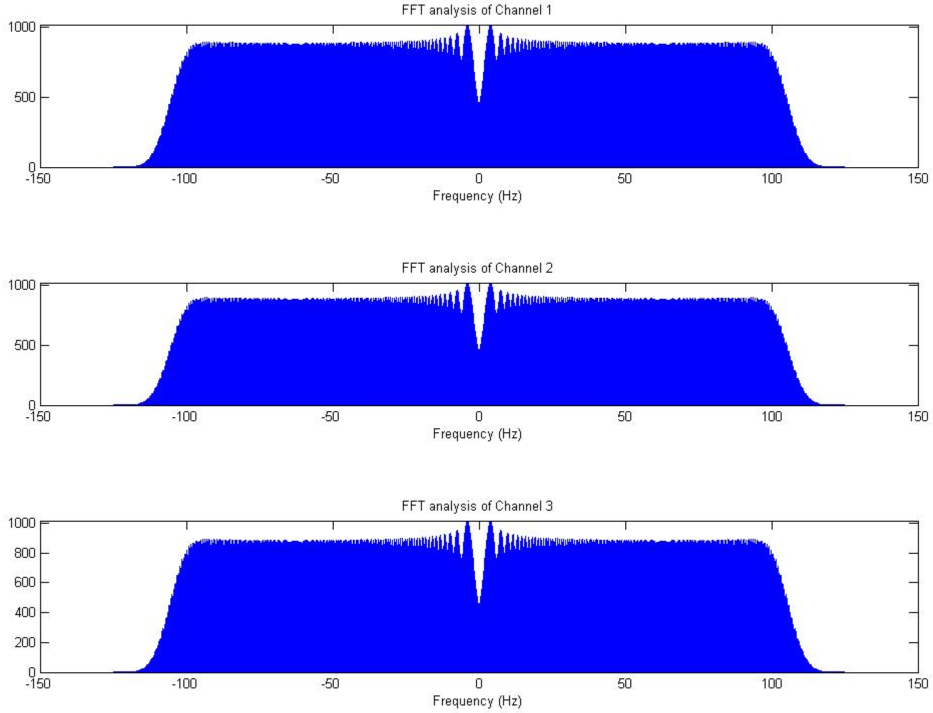

Figure 5. FFT analysis for frequency sweep 0.2-125 Hz with 1 Vpp amplitude

Shake table test

In July 2009, we conducted an electrodynamic shake table test in the Dept. of Civil Engineering at Caltech. The shake table input was fixed at frequencies between 0.1 and 90.0 Hz, and the ShakeBox response was compared with colocated Dytran piezoelectric accelerometers. Figure 3 shows the shake table test equipment and set up.

We ran the unidirectional shaker at 0.1, 0.5, 0.8, 1.0, 1.5, 1.2, 2.0, 5.0, 10.0, 25.0, 49.0, 50.0, and 90.0 Hz for between 10 seconds and two minutes using a sinusoidal wave as input. A two-minute ambient vibration test was conducted at the end of the test. Nine Dytran accelerometers were attached to the sides and top of a mounting plate (three in each direction). These were connected to a 24-bit Granite digitizer with GPS receiver. The Dytrans have flat response for 1-2000 Hz with a range of ± 50 g, and were calibrated at the factory in early 2009. During the tests, we compared the Dytran-Granite vs. ShakeBox performance in near-real time and observed close similarities in waveform shape and amplitudes. Though the input was a sine wave, the shaker appeared to give a little kick at each end of its travel distance. This produced additional peaks in the output seen on both the Dytrans and Colibrys sensors. Since we observed the response to these kicks on both sets of accelerometers, we concluded that it was not due to a fault in accelerometer response. Even though the channels were lined up parallel to and perpendicular to the direction of shaker motion (Figure 3 Left and Middle), the motion was not perfectly 1D, so a response was also observed in the other orthogonal channels but at lower amplitudes. Dytran-Granite timing was based on GPS time stamps and the ShakeBox timing was based on board time stamps with the PC clock, so Dytran-Granite timing was used as the reference start time.

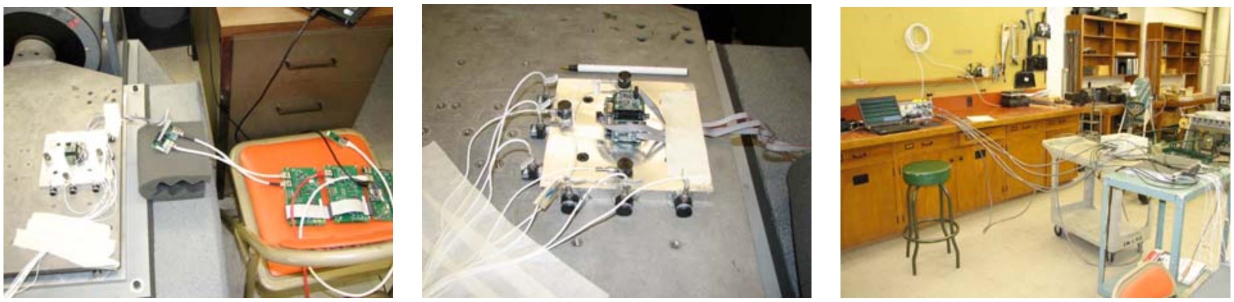

Figure 3. Left: Shake table top showing mounted steel plate with Dytran piezoelectric and Colibrys MEMS accelerometers and additional ShakeBox components on chair. Middle: Closeup of mounted plate with accelerometers. Right: 24-bit digitizer and PC recording setup for Dytran accelerometers.

For each frequency test we compared waveform shapes between Dytran-Granite and ShakeBox performance, expecting differences to be indications of questionable or faulty performance. Examination of absolute amplitudes showed that they were within 10% or better of each other, indicating good ShakeBox performance (Figure 4). The observed spectral peaks in the FFTs computed from the acceleration time series of both types of sensors also showed good agreement between the two systems.

Millikan library test

In October 2009, we conducted a ShakeBox performance test at the Millikan Library on the Caltech campus. The objective was to compare the ShakeBox performance vs. the permanent Episensor accelerometer performance

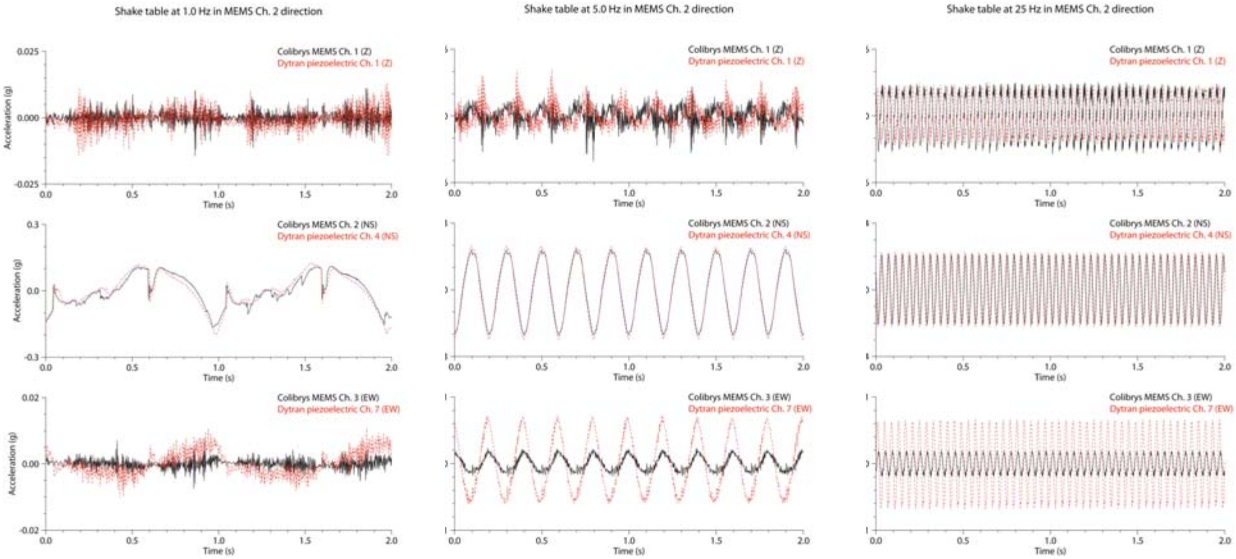

Figure 4. Shake table test results comparing ShakeBox (Colibrys MEMS: black curves) with Dytran piezoelectric accelerometer response (red curves), recorded at 100 sps. Left: 1 Hz sine wave input. Middle: 5 Hz input. Right: 25 Hz input.

during several forced vibration tests. The Episensor is a broadband force-balance accelerometer used in permanent wired structural arrays and has reliable, low-noise performance. An eccentric mass shaker is located on the Millikan Library roof and provided the excitation in a single horizontal direction at a time. Two Shakeboxes were colocated with three-component Episensor accelerometers in Millikan Library on the 9th floor and in the basement. Millikan Library is a 9-story reinforced concrete building consisting of both shear walls and moment frames. Shear walls dominate the east and west faces of the building and also line the elevator core in the center of the building. The shaker was run at frequencies between 1.0 Hz and 9.5 Hz and each ShakeBox response was compared with the colocated Episensor accelerometers.

The forced vibration tests consisted of an initial empty-buckets test (no weights added, resulting in minimum applied force), a full-buckets test (all weights added resulting in maximum applied force) in the east-west direction, and a full-buckets test in the north-south direction. The empty-buckets shake spanned frequencies from 1.0 to 9.5 Hz gradually over the course of approximately 40 minutes. The rate changed over the course of the sweep. The lower frequencies progressed at 0.05 Hz intervals every 20 seconds, from 2.5 Hz to 5 Hz progressing at 0.05 Hz intervals every 15 seconds, and from 5 Hz to 9.5 Hz progressing at 0.05 Hz intervals every 10 seconds. This frequency range covers the building's first EW modal frequency of 1.2 Hz (ambient), the first NS mode frequency of 1.7 Hz (ambient) and the first torsional mode frequency of 2.4 Hz (ambient). The second test consisted of a full-buckets shake (full set of weights for increased force resulting in temporary nonlinear response) for frequencies between 1.0 Hz and 2.5 Hz, particularly to excite the first EW frequency at 1.15 Hz (nonlinear response due to full set of weights). The sweep up to 2.5 Hz and back down to the starting frequency of 1.0 Hz took approximately 30 minutes. The EW full-buckets test also excited the torsional mode (2.3 Hz, nonlinear) in a narrow band around the mode progressing at a rate of 0.2 Hz intervals every 45 sec. At the end of this test we paused near the peak resonance for around a minute at both the first EW and torsional mode frequencies. The first EW frequency shake shows up primarily in the EW components of the accelerometers, and the first torsional shake shows up very clearly in both the EW and NS components. The third test consisted of a full-buckets frequency sweep in the NS direction for frequencies between 1.0 Hz and 1.8 Hz, particularly to excite the first NS frequency at 1.6 Hz (nonlinear). The NS full-buckets test excited the first NS frequency in a narrow band around the mode progressing at a rate of 0.2 Hz intervals every 45 sec. At the end of the test we paused again at resonance on our way back to 0 Hz. As the shaker frequency intersected these modes we got increased response resulting in increased amplitudes.

The recorded accelerations for both types instruments in the Basement and 9th floor locations are shown in Figure 5, plotted in the same comparable units (milli-g). Note that the amplitude scales are different for each component.

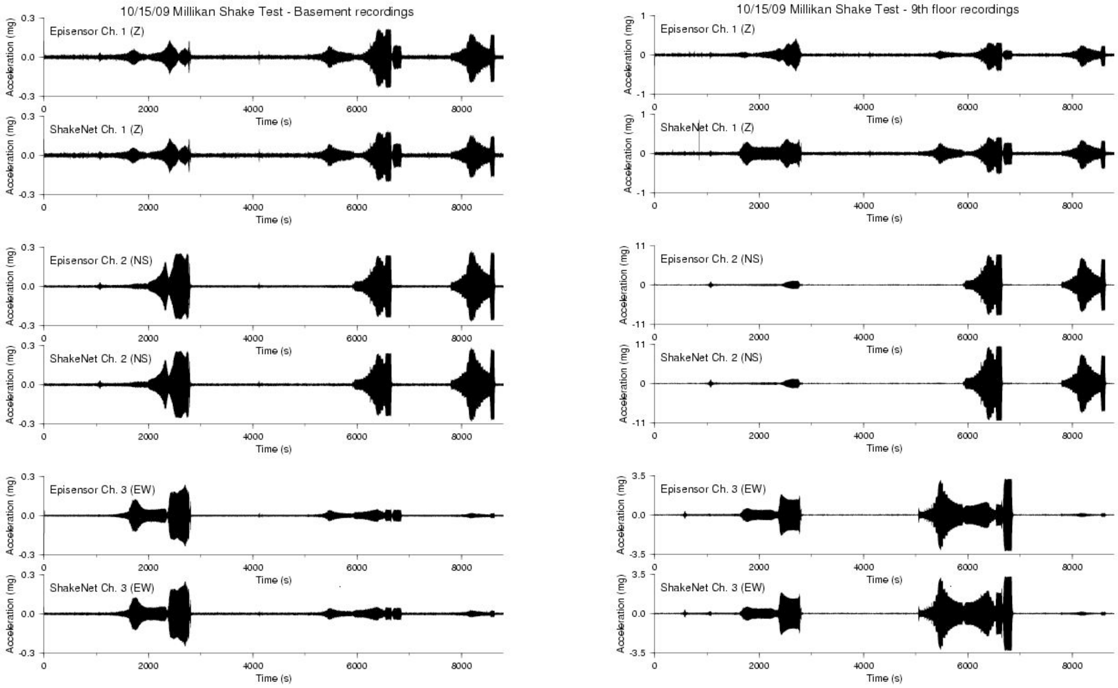

Figure 5. Acceleration responses due to forced vibrations recorded by the ShakeBoxes colocated with Episensors in the Basement (Left) and on the 9th floor of Millikan Library (Right).

Overall the response of the ShakeBox-Colibrys is quite similar to that of the Episensor-Granite except that the ShakeBox amplitudes are usually about 10-20% larger. This may be due to the lack of robust physical coupling of the ShakeBox with the floor slab in both locations (we placed our boxes on the floor whereas the Episensors are bolted into floor slabs or walls). In fact the amplitude difference is larger at the 9th floor where the shaking was stronger than in the basement.

SEI 06.4 Accomplishments

We have built a working sensing system - the ShakeBox, including both hardware boards and Tenet software tool suite.

We have conducted a series of experiments as described in section 3.

SEI 06.5 Future Directions

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. The current prototype is able to collect data from two ShakeBoxes sampling data at 125 Hz under each master. At this point we saturate the available radio bandwidth and hence cannot add anymore ShakeBoxes under this master. To overcome this limitation, we are implementing the Steim2 algorithm for compressing data on each ShakeBox prior to sending it to the master.

Time synchronization is required for correlation of data collected across ShakeBoxes. Since the ShakeBoxes will be placed inside the building or structure, using GPS for time synchronization cannot be counted on. We use network time synchronization over the mote and master cloud. Currently we use network time protocol (NTP) for master cloud time synchronization and Flooding Time Synchronization Protocol (FTSP) for time synchronization over the mote cloud. We are developing a method to time-synchronize the mote and master cloud over USB. This becomes challenging due to the requirement of only a few millisecond error margin for time synchronization imposed by domain experts.

After the integration test of the system as a whole, we plan to deploy 40 ShakeBoxes in realistic environments, for example, the Factor building at UCLA, the Santa Ana River Bridge and the Seven Oaks Dam. We will test the working flow of the whole system and the fidelity of the sampling data collected.