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Multi-scale Wireless Sensor Node for Impedance-based SHM and Low-frequency Vibration Data Acquisition

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ABSTRACT: This paper presents recent developments in an extremely compact, wireless impedance sensor node (WID3, Wireless Impedance Device) at Los Alamos National Laboratory for use in impedance-based structural health monitoring (SHM), Sensor diagnostics and low-frequency vibrational data acquisition. The current generation WID3 is equipped with an Analog Devices AD5933 impedance chip that can resolve measurements up to 100 kHz, a frequency range ideal for many SHM applications. An integrated set of multiplexers allows the end user to monitor seven piezoelectric sensors from a single sensor node. The WID3 combines on-board processing using an Atmega1281 microcontroller, data storage using flash memory, wireless communications capabilities, and a series of internal and external triggering options into a single package to realize a truly comprehensive, self-contained wireless active-sensor node for SHM applications. Furthermore, we recently extended the capability of this device by implementing low-frequency analog to digital and digital and analog converters so that the same device can measure structural vibration data. The WID3 requires less than 70 mW of power to operate, and it can operate in various wireless network paradigms. The performance of this miniaturized and portable device is compared to our previous results and its broader capabilities are demonstrated.

1 INRODUCTION

Structural health monitoring (SHM) is the process of detecting damage in structures. The goal of SHM is to improve the safety and reliability of aerospace, civil, and mechanical infrastructure by detecting damage before it reaches a critical state. A more detailed general discussion of SHM can be found in Farrar et al. (1999). The implementation of SHM is an integrated paradigm of networked sensing and actuation, data interrogation, and statistical assessment that treats structural health assessments in a systematic way. An appropriate sensor network is always required as a first line of attack in observing the structural system behavior in such a way that suitable signal processing and damage-sensitive feature extraction on the measured data may be performed efficiently.

In order for any SHM system to be successful, there must be a reliable stream of operational data available for analysis, requiring little or no intervention on the part of engineers to obtain such data. This study addresses the reliability and longevity issues surrounding the collection of data from a remote civil infrastructure site with long intervals between on-site maintenance of the sensing and data acquisition systems. Such a system requires a robust sensor network.

1.1 *Networking for SHM*

Sensor networks contain four main components: the sensing mechanism, computation, telemetry, and power management (Farrar et al. 2006). In many SHM applications, including that applied in this work, a fifth component—actuation—is also required. Such applications are known as active sensing applications because a user-prescribed excitation signal is applied to the system via the actuator and then detected by the sensor network after interaction with the system.

The most common general architecture that integrates these components is a conventional wired sensor network. Here, individual sensing components typically stand alone and are wired to a centralized data processing and multiplexing unit. Each sensor is independent of other sensors in the network, and controlled synchronized interrogation of the entire network is achieved only through the central unit. Limitations of such systems are that they are difficult to deploy in a retrofit mode because they usually require a power source, which is not always readily available in existing structures. Also, these systems are one-point failure sensitive, and one wire may be as long as a few hundred meters. In addition, the deployment of such system can be challenging with potentially over 75% of the installation time attributed to the installation of system wires and cables for larger scale structures such as those used for long-span bridges (Lynch et al. 2003).

While the majority of permanently installed sensor networks today employ this wired architecture, development and deployment of wireless sensor networks has exploded in recent years. Most wireless sensor network paradigms fall into one of the categories outlined by Farrar et al. (2006). However, while much exploratory work has been done to assess the feasibility of wireless networks for SHM, very little has been done toward a permanently installed wireless sensor network for SHM.

1.2 *Paper outline*

This paper addresses several of the requirements for a robust and reliable wireless sensor network for SHM permanently installed in a remote location. The key components required for such an installation addressed in this paper are the measurement devices (sensor nodes), the permanently installed sensors, and the specific networking strategies required to collect and analyze the data. Laboratory proof-of-concept results for various aspects of the sensing system are presented, as well as experimental results from field tests at the proposed permanent wireless SHM system installation site in southern New Mexico.

2 MEASUREMENT DEVICES

2.1 *Conventional Data Acquisition*

In the first phase of the long-term sensor monitoring project, data were collected using a National Instruments [MODEL NUMBER] data acquisition system.

2.2 *Wireless Hardware and Operational Concept*

The impedance method (Park et al. 2003) takes advantage of the electromechanical coupling between the element and the structure such that damage-induced changes to the structure's mechanical impedance correlate with measurable changes to the element's electromechanical impedance; the method can also be used for sensor self-diagnostics (Park et al. 2006a, Park et al. 2006b).

The wireless impedance device (WID) was originally developed based on capabilities demonstrated in previous studies of the impedance-based structural health monitoring method (Park et al. 2003). The impedance method uses high-frequency vibrations to monitor for changes in structural impedance that would indicate damage. The impedance method can be implemented with relatively low power compared to other active-sensing SHM techniques such as Lamb wave-based methods. The impedance method also has applications in sensor self-diagnostics to determine the operational status of piezoelectric active-sensors used in SHM (Park et al. 2006a).

Three generations of the WID have been developed and field-tested by our research team (Mascarenas 2007, Overly 2008). The WID2 was developed to address some of the limitations of the previous version, which could monitor only a single sensor, had limited triggering capabilities, and used telemetry components with high power demands. The WID3 has further extended capabilities with advanced communications, increased triggering options, local data storage, and multiple powering options including a variety of energy harvesting sources. The WID3 can self-configure into a network with neighboring sensor nodes at fixed time intervals or in the presence of a 'mobile-agent' that interrogates the sensor network.

In addition to improving the capabilities of the previous WID versions, the WID3 has been designed to function as part of a modular hardware platform that incorporates other sensing modalities on separate boards, including time-domain measurements. By combining modules, resources such as telemetry, processing, data storage, and respective measurement capabilities of each module can be shared, resulting in a highly functional sensor node. This integrated sensor node combines both actuation and sensing capabilities in a single package with the ability to implement multiple SHM techniques for the rapid health assessment of civil, aerospace and mechanical infrastructure.

2.3 *WID3 hardware and capabilities*

The major hardware components of the WID3 are shown in. The WID3 uses a ZigBit module which integrates an Atmel ATmega1281v microcontroller (μCu) with an Atmel AT86RF230 radio in a single integrated circuit (IC). The μCu is part of Atmel's 8-bit AVR line, and it contains 128kB of flash memory for algorithm and code storage. It also contains 8kB of SRAM for program execution. The AT86RF230 is an 802.15.4 compliant radio, and it uses an open media access control (MAC) table distributed by ZigBit. The availability of the MAC table facilitates programming for robust data transmission. The AT86RF230 has very low energy requirements and requires few external components, making it particularly attractive for an SHM device.

The key measurement component the WID3 is the AD5933, an IC for impedance measurement. This IC has the ability to measure electrical impedance up to 100 kHz. The AD5933 can only measure a single channel, but the WID3 is equipped with two low-power and low-resistance multiplexers, which are indicated in Figure 1. Each multiplexer has eight total inputs, providing for four impedance measurement ranges and the ability to measure seven sensors. One of the sensor ports is dedicated to a calibration cycle, reducing the number of sensor channels from eight to seven.

There are two main options for data storage on the WID3: internal EEPROM on the ATmega1281v, and a flash memory module, the Atmel AT26F004. The data storage available in these locations is 8kB and 512kB, respectively. The WID3 has very low maximum power consumption in spite of the active nature of its measurements. Operating at 3V, the WID3 takes 16 seconds to measure four sensors with 100 points and four averages per point. With data reduction, only a few seconds would be required to transmit the data, or a few microseconds to store the data locally. The current draw can also be reduced to approximately 0.01mA with proper use of sleep modes. With these steps, the WID3 could take, analyze, record and send one measurement per day for over 5 years on two conventional AA lithium batteries. At this extremely low power level, the WID3 could also be powered by a wide range of energy harvesting methods.

The WID3 can be woken from sleep states in two ways. The WID3 includes a low frequency wake-up chip, the Atmel ATA5283, that monitors for a 125 kHz wake-up signal. This monitoring occurs at very low current draw (0.1μA) and short range (2.5m). The chip and inductor coil a ntenna are indicated in Figure 1. This wake-up method would be used by a mobile-agent for recording on-demand measurements. Secondly, an internal timer in the ATmega1281v can wake up the WID3 at intervals on the order of a few seconds to a few weeks. With these solutions available, the WID could run in low duty cycle operation for decades on a limited power supply.

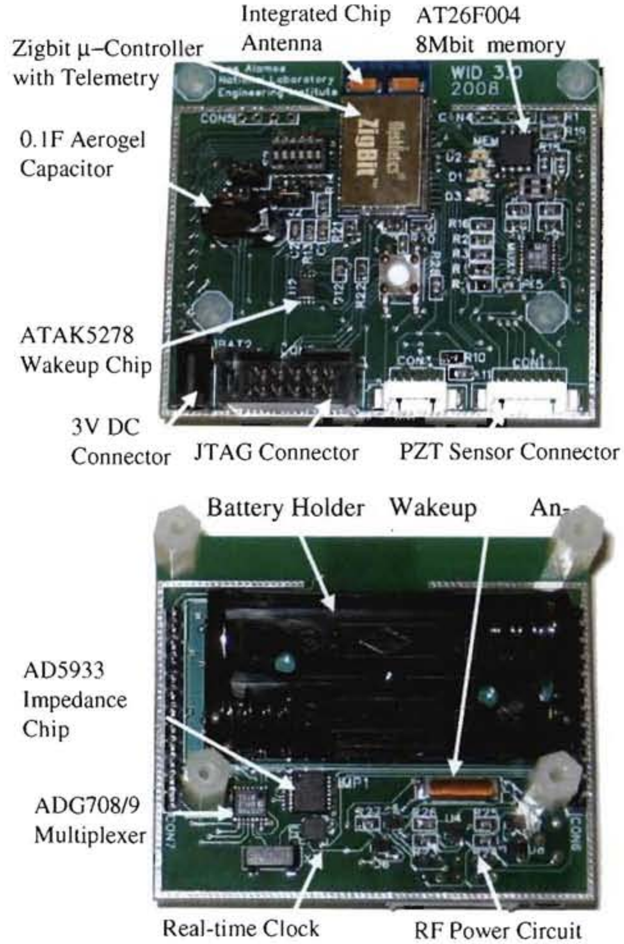

Figure 1. Prinicpal components of the newest generations Wireless Impedance Device (WID3).

3 SENSOR DIAGNOSTICS

The success of any permanently installed SHM system is dependent on the ability to accurately monitor the health of the sensors themselves, so that deviations from baseline measurements can be confidently attributed to structural changes rather than sensor or system malfunction. This section presents the sensor diagnostic capability of WID3, which is able to perform sensor diagnostics to determine whether the installed sensors/actuators are operational.

Such validation is critical during the SHM system operation, and arrays of PZT active-sensors lend themselves particularly well to diagnostic interrogation without regardless of the condition of the structure on which they are installed. The basis of this method is to track the capacitive value of PZT transducers, which manifests in the imaginary part of the measured electrical admittance (Park et al. 2006a, 2006b). Both degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure can be identified by this process.

Although temperature variations manifest themselves in similar ways that sensor failures are manifest. In order to maintain robustness to temperature fluctuations, we have developed an efficient signal processing tool that enables the identification of a sensor validation feature that can be obtained instantaneously without relying on pre-stored baselines and be immune to temperature variations (Overly et al. 2009). The theoretical base of the sensor diagnostics and the signal processing tools is detailed in Park et al. (2009) and Overly et al. (2009). These diagnostics tools are incorporated in the SHMTools software package, currently under development by the authors. These tools were extended to utilize data collected with the WID3 system.

A sensor diagnostics demonstration plate, shown with the WID3 in Figure 2, was constructed to test the sensor diagnostics capability. Twelve circular piezoelectric patches are mounted using super-glue on one surface of an Aluminum plate (30 x 30 x 1.25 cm). The size of each circular PZT patch is 5.5 mm diameter with 0.2 mm thickness. Patches had different bonding conditions, including perfect bonding, debonding, and sensor breakage. Six patches were bonded perfectly, three of them partially bonded with 25%, 50%, and 75% debonded area, and the remaining three were fractured with 25%, 50%, and 75% sensor loss. After installation, admittance measurements were taken using the WID3 in the frequency range of 5-30 kHz for each PZT patch.

Figure 2. Sensor Diagnostics demonstration plate with healthy, de-bonded, and broken sensors

The experimental results are illustrated in Figure 3 through Figure 6. For both measurement sets, the WID3 was connected to five healthy sensors and two faulty sensors. With de-bonded sensors, the slope of the measured admittance is greater than that for perfectly bonded sensors. As the de-bonded area increases, there is a corresponding increase in the slope, which is visible in Figure 3. With broken sensors, the slope of the measured admittance is less than that for perfectly bonded sensor, a result of the reduced capacitance of the now smaller sensor. In Figure 4, one can observe that the downward shift of the slope of the imaginary admittance is proportional to the breakage percentage.

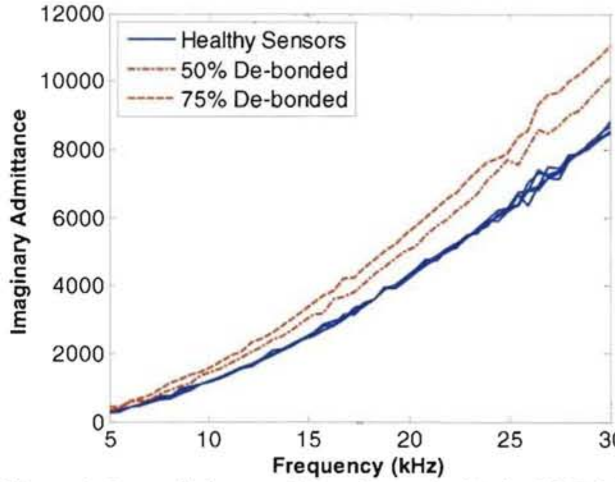

Figure 3. Raw admittance data collected with the WID3 for de-bonded sensors.

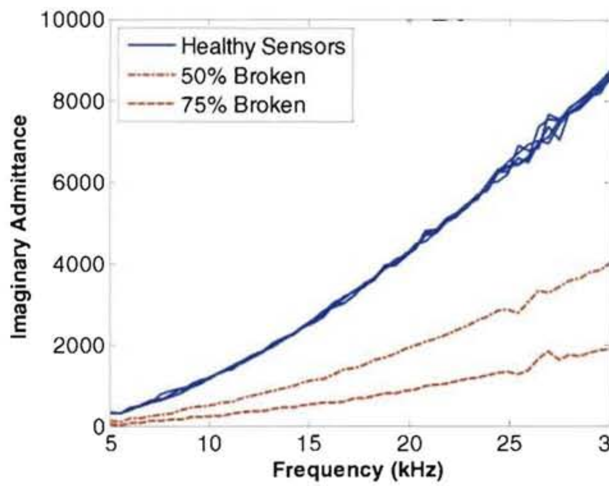

Figure 4. Raw admittance data collected from the WID3 for broken sensors.

Figure 5 and Figure 6 Illustrate the results from the SHMTools sensor diagnostics functions using data collected by the WID3. All the sensor conditions were correctly identified using the baseline-free algorithm developed by Overly et al. (2009).

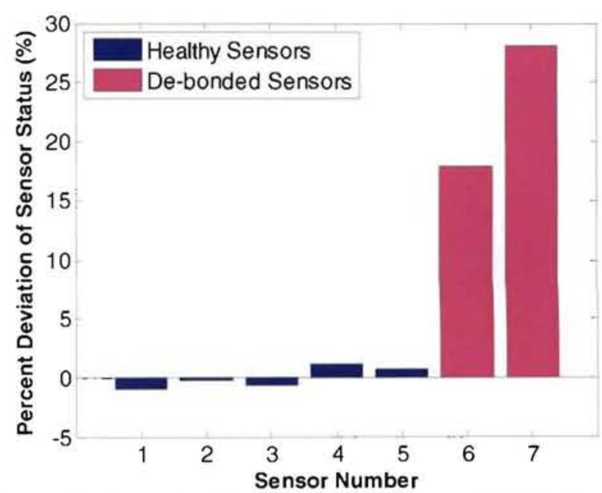

Figure 5. Auto-classification results from SHMTools for de-bonded sensors.

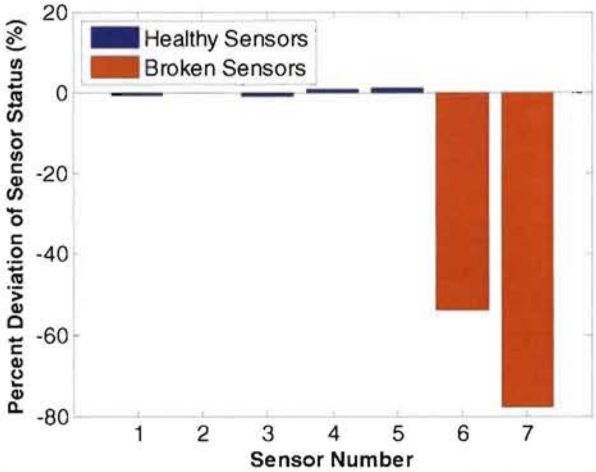

Figure 6. Auto-classification results from SHMTools for broken sensors.

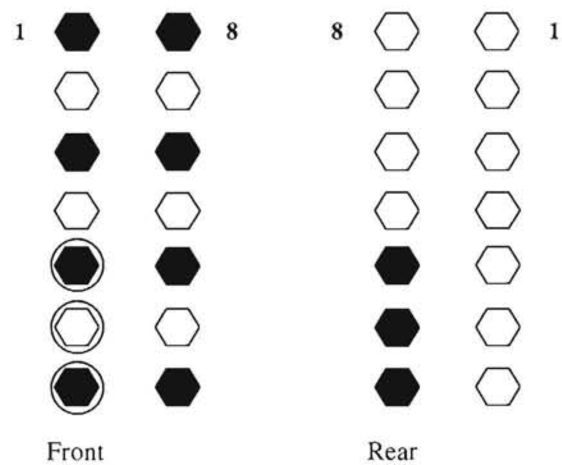

Figure 7. Bolt pattern and instrumentation diagram.

4 FULL-SCALE BRIDGE TESTING RESULTS

The test site chosen for full-scale SHM of a civil infrastructure installation is the Alamosa Canyon Bridge, located in southern New Mexico, USA. This bridge has been decommissioned and made available by the New Mexico Department of Transportation as a test-bed for structural health monitoring systems. The bridge itself is a traditional steel girder construction with a concrete reinforced deck that is approximately 25 cm thick.

In this phase of testing, the long-term viability of installed sensors is being explored. In October 2009, 28 lead zirconate titanate (PZT) patches were permanently installed on the bridge. A total of 14 sensors were installed on two adjacent joints. One instrumented joint is on the west side (exterior) of the bridge, and the other joint is on the interior of the bridge. Each joint is bolted together with 14 bolts. A diagram of the bolt pattern and sensor installation detail is shown in Figure 7. The bolts are numbered vertically beginning with bolt 1 on the upper left of the front of the joint. The solid fill indicates a PZT installed on the nut or bolt head, and a circle indicates a PZT installed on the vertical surface adjacent to the bolt.

4.1 *Baseline Tracking*

In order to apply a long term SHM system that utilizes comparisons to baseline measurements, it is necessary to identify changes to measurements that result from daily and seasonal environmental variability. In moving toward a permanently installed SHM system, baseline measurements were collected from permanently installed PZT patches over a one-month interval. The first set of data was collected in October 2009, immediately following the sensor installation, and the second set of data was collected one month later in November 2009. Baseline tracking results are presented using data collected from the conventional data acquisition system (NI PXI-1042Q).

Figure 8 shows the real part of the measured admittance for six bolts measured in both October and November 2009. Baseline data were obtained at each test for bolts 3, 5, 7, 10, 12, and 14. In the case of bolts 3, 5, and 7, the nuts were alternatively loosened and tightened between baseline readings, while in the case of bolts 10, 12, and 14, the nuts remained tight for all baseline readings. The results seen in Figure 8 demonstrate the repeatability of baseline measurements, even after loosening and tightening the nuts. Shifts in amplitude are indicative of temperature changes, but the overall shape of each waveform remained the same from one test to the next.

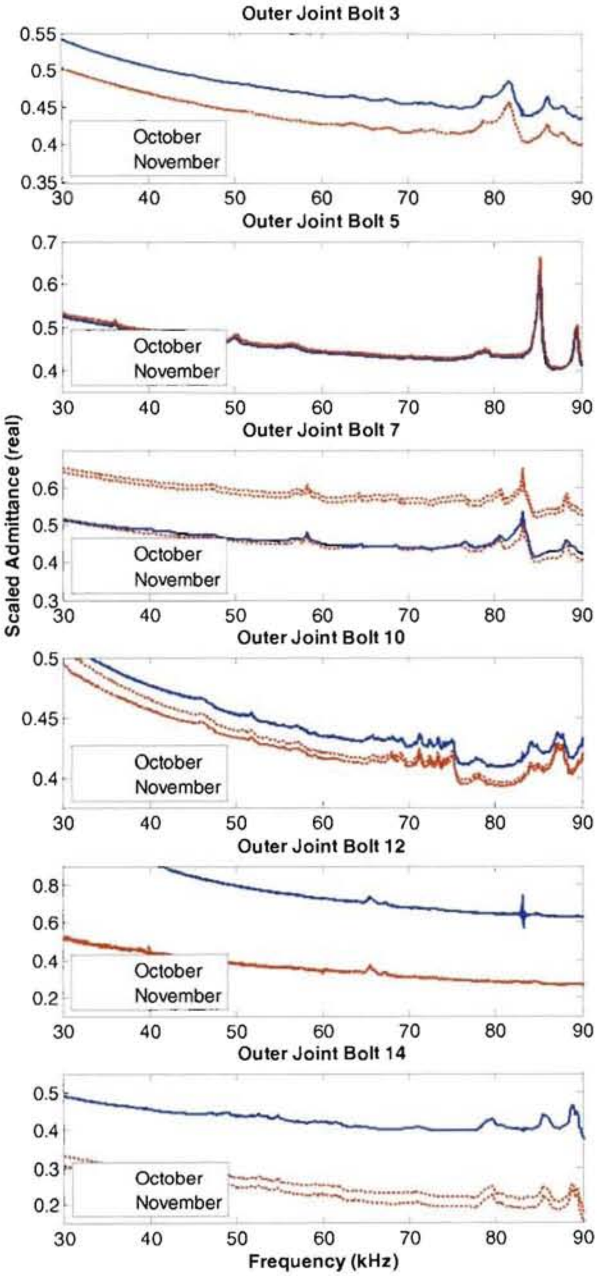

Figure 8. Baseline impedance measurements for outer joint bolts in October and November 2009.

4.2 *Damage Identification*

Damage was introduced to the bridge in the form of loosening the instrumented nuts. Detection of bolted joint preload loss has been well demonstrated (Mascarenas et al. 2009, Overly et al. 2008, Taylor et al. 2009). It is not the goal of this study to demonstrate the ability to detect loss of bolt preload, but to investigate the viability of a permanently installed SHM system in a remote location. However, it is useful to demonstrate the ability of the SHM system to detect a given type of damage reliably prior to testing the longevity of a permanently installed SHM system.

Selected damage identification results are shown in the following figures. Figure 9 shows results from bolt 3 on the inner joint, while Figure 10 shows results from bolt 14 on the inner joint. In each case, impedance measurements were taken using the WID3 over a range of 80 to 100 kHz. Initial baseline measurements were made followed by damaged state measurements in two states: State 1, wherein the nut was just broken loose, but could not spin freely; and State 2, wherein the nut was completely loose and could spin freely. The nut was then retightened and another baseline measurement was taken.

In the case of bolt 3, shown in Figure 9, the second baseline measurement returned to the same general waveform as the first, and the damaged State waveforms are identifiable as damaged by peaks at around 88.5 kHz and 86.5 kHz for State 1 and State 2, respectively. In the case of bolt 14, shown in Figure 10, the second baseline measurement again returned to the same general waveform as the first, and the damaged State waveforms are identifiable as damaged by peaks at around 86.5 kHz and 88 kHz, respectively.

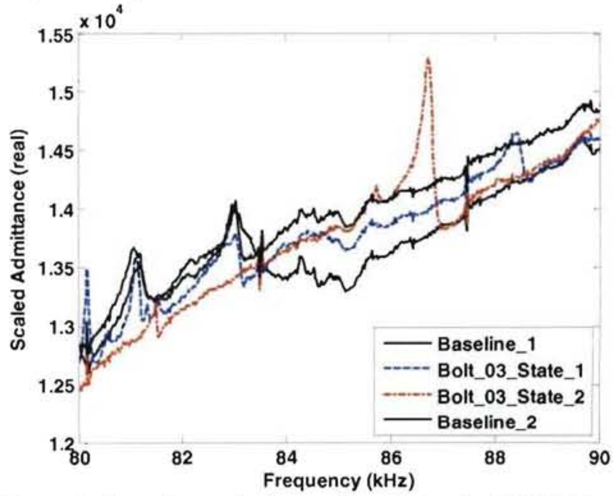

Figure 9. Experimental data collected by the WID3 for inner joint bolt 3 in several states.

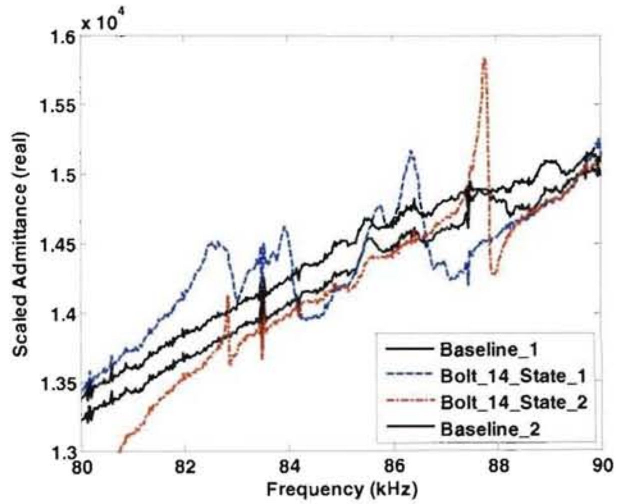

Figure 10. Experimental data collected by the WID3 for inner joint bolt 14 in several states.

5 NETWORKING FOR SHM SYSTEMS

Introduce SHM networking paradigms.

5.1 *Local Networking with Data Aggregator*

A simulated permanent installation network test was performed at the Alamosa Canyon Bridge in 2008 (Taylor et al. 2009), using multiple local networks with a data aggregator present in each network. The schematic of the local network is shown in left-hand image in Figure 11. Maintaining separate local networks has several advantages with very large structures in that additional routers to transmit data over large distances are not required. Furthermore, immediately following a catastrophic event, the loss of a single node could not destroy the entire network. This networking approach is more efficient with active-sensing SHM techniques, as those techniques are local area monitoring techniques, as opposed to global structural monitoring systems.

Three separate local networks were implemented on the bridge, each operating using a different frequency band. Each coordinator was constantly powered, and the end devices operated in an extremely low-power mode, awakening at regular intervals to take measurements, and transmit the results to the coordinator. The data aggregators stored received measurements on non-volatile until the data were retrieved by the mobile-agent. The setup of this testing on the bridge is shown in the right-hand image of Figure 12.

This local network approach is somewhat unique for SHM applications, as SHM sensors and sensor nodes do not have to be deployed on to the entire structure. Instead, the nodes could be installed on critical areas of a structure, following the concept of the active-sensing SHM strategy. The sensor node does not have to attempt to identify any neighbor nodes or relay the data, as in the case of the hopping networking protocol. Furthermore, the sensors can be more optimally placed on a structure to improve the performance of the SHM process.

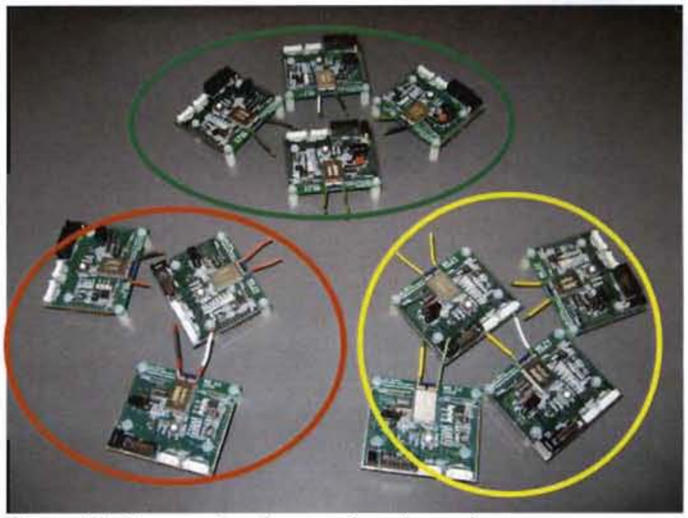

Figure 11. Separate local networks schematic

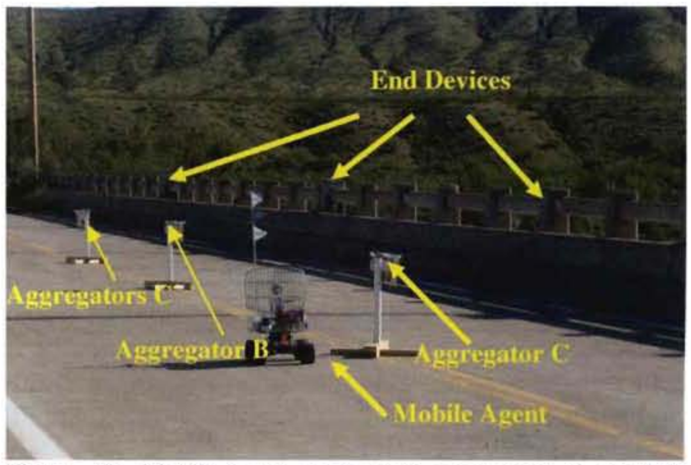

Figure 12. Mobile-agent approaches aggregator to retrieve data.

5.2 *Proposed long-distance monitoring platform*

A significant extension to the simulated permanent installation would be required in order In order to provide a reliable stream of operational measurement data from remote monitoring locations to decision-making computers and analysts. Namely, data must be transmitted off-site on a regular basis for analysis using either a cellular or satellite data uplink. To achieve this end, a tiered networking scheme must be implemented, as shown in Figure 13. In the simplest implementation, a local wireless network of sensor nodes will wake up on schedule, perhaps twice per day, take measurements, and transmit those measurements to the data aggregator, which may also perform some simple preprocessing operations on the collected data. The data will then be transmitted via a cellular or satellite network connection to a repository available to analysts (which may be automated) on the internet.

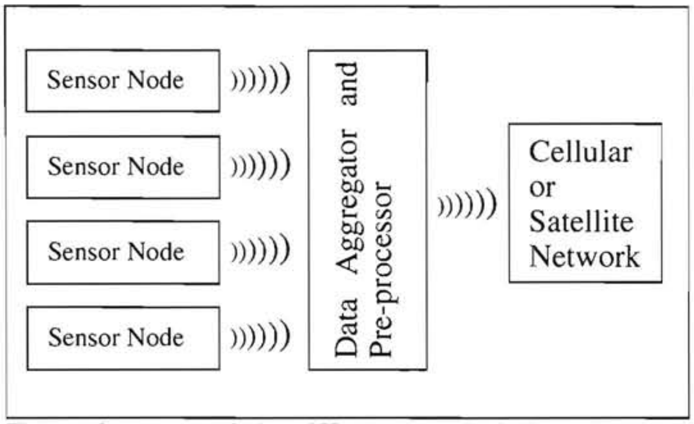

Figure 13. Remote wireless SHM system block diagram.

6 FUTURE WORK

The sensors utilized for this study are currently installed on the bridge, and further baseline measurements will be obtained on approximately a monthly basis, in order to further validate the legitimacy of such a long-term SHM system installation. Once the repeatability of the baseline measurements and the ability to reliably detect damage have been validated over the course of several months, a local wireless network will be installed permanently on the structure, along with a cellular or satellite uplink, which will provide a steady stream of data available on the world wide web.

7 SUMMARY

[description of application of WID3 to permanent SHM installation]

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