# Wireless Intelligent Sensor and Actuator Network (WISAN): a scalable ultra-low-power platform for structural health monitoring

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#### **ABSTRACT**

This paper presents Wireless Intelligent Sensor and Actuator Network (WISAN) as a scalable wireless platform for structural health monitoring. Design of WISAN targeted key issues arising in applications of structural health monitoring. First, scalability of system from a few sensors to hundreds of sensors is provided through hierarchical cluster-tree network architecture. Special consideration is given to reliable delivery of wireless data in real-world conditions. Second, a possibility of autonomous operation of sensor nodes from energy harvesters is ensured through extremely low power consumption in operational and standby modes of operation. Third, all the sensors and actuators operate in globally synchronized time on the order of a few microseconds through utilization of the beaconing mechanism of IEEE802.15.4 standard. Fourth, depending on application requirements, the system is capable of delivering real-time streams of sensor data or performing on-sensor storage and/or processing with result transmission. Finally, a capability to work with heterogeneous arrays of sensors and actuators is ensured by a variety of analog and digital interfaces. Results of experimental tests validate the performance of the WISAN.

Keywords: wireless sensor networks, wireless structural health monitoring, IEEE802.15.4, ambient vibrations.

#### 1. INTRODUCTION

The need for structural health monitoring and condition-based maintenance is well established in research literature <sup>1-4</sup>. Targeted goals include eliminating loss of life and economic loss connected to catastrophic failures and reducing structure's life cycle costs. An automated or an automatic monitoring system would largely eliminate the subjectivity of visual inspections and provide objective and quantifiable results. Wireless and MEMS-based sensor technologies present an appealing alternative to traditional tethered monitoring systems by offering longer sensor life spans, lower energy consumption, low equipment costs and lower installation costs. The lower costs of wireless and MEMS-based monitoring systems will eventually allow moving toward pervasive monitoring of civil infrastructure. As research area of structural health monitoring matures and moves into the application arena, many new technologies emerge that address various needs of structural health monitoring. Some systems <sup>5</sup> utilize well-established consumer-oriented technologies like IEEE802.11a/b/g wireless networks to collect data from bridges and buildings. Such systems have the advantage of readily available and inexpensive hardware and software but often lack in the functionally required by a specific method of structural health monitoring or pose high energy consumption requirements.

A significant effort goes into developing custom-tailored solutions based on proprietary technology <sup>5-9</sup>. A specialized solution provides a much better fit to a specific monitoring methodology and can address the limitations posed by wireless consumer networks. In some situations a custom solution is the only choice for a demanding application, for example wireless ultrasonic damage detection. Energy available to power the sensors, microcontrollers and the radio transceiver still remains the major design constraint that limits practical applicability of many devices. As an example, a FPGA-based design is easily programmable and is capable of providing the user with advanced functionality, but would normally require a significant amount of energy, which may not be readily available on a civil structure like a bridge.

Another drawback of a custom solution also becomes obvious when multiple sensors from different vendors may need to be integrated in a monitoring system.

In our earlier work <sup>12, 13</sup> we suggested a concept of Wireless Intelligent Sensor and Actuator Network (WISAN) that targets a variety of monitoring applications. The attempt was made to pose requirements to a wireless system that would eventually allow for fully autonomous, unattended and pervasive monitoring. This paper presents the work in progress, where many of initially specified requirements have been satisfied.

## 2. REQUIREMENTS FOR WIRELESS SENSOR NETWORK

This section presents a condensed set of requirements posed to the wireless sensor network. The reason to rethink the requirements is simple: the sensor network protocols like TinyOS have been originally designed with event-driven, low duty applications in mind and may not be the best choice for monitoring of civil infrastructure.

The underlying assumption is that an ideal monitoring system would require virtually no maintenance and only remind of its existence when either the structure needs maintenance or the system itself malfunctions to a critical degree. The monitoring system would operate autonomously, without a need for a human operator and unattended. This includes eliminating the battery replacements required by most wireless systems today. The following is a list of requirements that we originally suggested in <sup>12, 13</sup>:

- 1. Low-cost autonomous data acquisition at the expense of 1-2% total structure cost. It is reasonable to assume that the cost of monitoring system should not significantly raise the total price tag of a structure. Given an approximate construction cost of highway bridge <sup>14</sup> in the range \$200,000-\$800,000, the cost of instrumenting a bridge with sufficient number of sensors (20-100) should be in the range of \$2000-\$16000, which implies per sensor cost of \$100 or lower. Such low costs can be achieved though utilization of massmarket technology and standardized solutions. WISAN utilizes low-cost components from Chipcon (IEEE802.15.4 transceiver), Texas Instruments (MSP430 series microcontroller) and low-cost, high accuracy MEMS sensors that allow reaching the target cost range even in prototype production runs.
- 2. Self-sustaining power sources and minimization of energy consumption. Energy remains a bottleneck for monitoring applications. The cost of replacing the batteries in wireless sensors would quickly overrun the savings from wireless technology. Wired energy delivery suffers from the same drawbacks as wired instrumentation. Ambient energy harvesting is capable of providing an endless supply of energy, but at very small power levels. Minimization of sensor energy consumption is imperative for energy harvesting technologies. WISAN is based on an ultra-low power microcontroller from Texas Instruments with one of the best performance/energy ratios on the market today. A WISAN v1.1 sensor node consumes just a few microwatts (~10uW) of energy in standby operation and is capable of being sustained by ambient energy sources.
- 3. Low-latency, scalable network with globally synchronized data. Timely delivery of critical information is extremely important for monitoring applications. Ideally the wireless network should behave in a manner similar to a wired system, where the data samples from different channels are normally synchronized in time and carry very little latency. The sampling synchronization error between any two nodes of the network should be significantly less than the period of the signals being acquired. The number of nodes in the network can vary from application to application and should not impact the functionality of the network. WISAN employs a variety of techniques to support this functionality. Global time synchronization is achieved through beacon tracking and (work in progress) synchronization to accurate time signals from GPS satellites. Low latency of communication is achieved through intelligent bandwidth scheduling (in preparation for publication) that minimizes collisions in the network, reduces the amount of retransmission and thus improves latency of the system and minimizes energy consumption of sensor nodes.
- 4. Fault-tolerant, reliable and secure communications in the Industrial, Scientific and Medical (ISM) band. In the modern society, a wireless sensor network must coexists with other devices functioning in the ISM range of radio frequencies, like microwaves, cordless phones, Bluetooth and WiFi devices, etc. The network

- should also provide a fault-tolerant, reliable, and secure way of communication. WISAN is based upon an IEEE802.15.4-compatible transceiver which addresses these issues.
- 5. Energy-efficient distribution of computational load and on-sensor intelligence. Based on monitoring methodology it may be efficient to perform some simple, energy efficient operations like compression on a sensor node or delegate computations to more powerful node with abundant power from the power grid. The goal is to minimize the total energy consumption or latency of the system. WISAN's efficient microcontroller allows performing energy-efficient computations (such as computing variance or standard deviation) directly on the sensor node.
- 6. Self-localization of sensor nodes. Tracking device placement in large networks can be quite challenging. Self-localization of sensor nodes allows delegating this task to the nodes themselves. A possible self-localization methodology is based on Radio Signal Strength Indicator (RSSI). WISAN's transceiver is capable of RSSI measurements and supports such localization methods.
- 7. **Damage detection, localization and quantification from ambient energy.** The SHM system should be built around sensors and monitoring methods that do not require significant energy expenditures to perform measurements and excitation of the structure (for example, the energy to excite a piezoceramic transducer, scaled up to hundreds transducers on a bridge, is very high), but function by capturing and analyzing the ambient response of the structure. By using the ambient energy such as excitation from traffic, wind, and microtremors the total energy requirement of the system can be reduced.

#### 3. WISAN HARDWARE PLARFORM

The hardware platform for WISAN sensor nodes is built taking the above requirements in mind. The block diagram of a WISAN sensor node is shown in Fig. 1 and a front view of the WISAN v1.1 implementation is shown in Fig. 2. The main concept of the design is extendibility for various applications.

Data acquisition modules are built around an ultra-low-power microcontroller MSP430F1611 from Texas Instruments <sup>10</sup>. The data acquisition modules each provide up to six 12-bit analog-to-digital channels and two 12-bit digital-to-analog channels. External 16-and 24-bit ADCs can be interfaced via extension connectors on the board. The extension connectors also allow access to 16 general-purpose digital input/output channels, including interrupt request pins and a JTAG debugging interface.

WISAN sensor nodes have been interfaced to SPI humidity/temperature sensors, storage cards (1Gb miniSD), external LCDs and personal computers (USB/Bluetooth serial interface). The modular design allows a scalable design with a flexible number of input/output channels and relieves the network protocol controller from executing the signal processing tasks.

The microcontroller also connects to the network interface chip via an internal SPI bus. The network interface module implements the network protocol based on IEEE 802.15.4 MAC standard. A 2.4 GHz module CC2420 from Chipcon <sup>11</sup> is used for the radio interface. The CC2420 is a low-power, low-cost, IEEE 802.15.4 compliant transceiver designed for RF applications in the 2.4 GHz unlicensed ISM band. The transceiver module provides 16-channel direct sequence spread spectrum modem

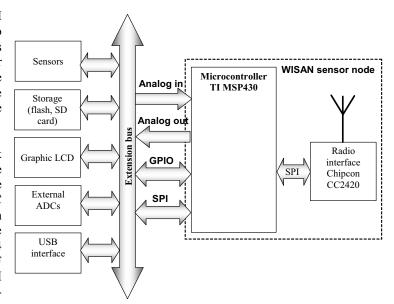


Fig. 1. Block diagram of a WISAN sensor node.

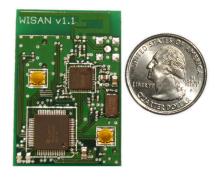


Fig. 2. Front view a WISAN sensor node.

with 2 Mchips/s and 250 kbps effective raw data rate, low power consumption (RX: 60 mW, TX: 52 mW), effective range 10 to 75 meters, programmable output power, hardware MAC encryption and authentication (AES-128), signal strength indicator and battery monitor. The MAC implementation from Chipcon has been modified to run on MSP430 processors and new functionally introduced to satisfy the set requirements.

The WISAN platform has ultra-low energy consumption in sleep modes (<10uW). For a battery-powered device, the current drawn by the sensor node in sleep with a real-time timer running is actually below the self-discharge current of a battery. Energy consumption in active (powered up) mode depends on what components are active at the time. With just the processor core active, a MSP430 consumes about 0.84mW at 1Mhz or 7.5mW at 8Mhz. Active internal or external ADCs, DACs, storage and other devices increase

total energy consumption.

The low energy consumption enables truly autonomous and continuous operation from an energy-harvesting device. In practical terms, a virtually maintenance-free SHM system could be created by utilization of electro-mechanical or piezoelectric power generating devices for powering of the WISAN nodes.

#### 4. WISAN SOFTWARE PLARFORM

The network stack is responsible for the functionality provided by the sensor network and services available to end user. As the hardware platform defines the minimal energy consumption of a sensor node, the protocol stack defines energy that a node will actually spend sending the data over the network.

WISAN protocol stack is built around IEEE802.15.4 MAC layer which may be considered a subset of Zigbee specification. The protocol software is currently evolving, gaining additional features and new capabilities. The stack is based on cluster tree architecture <sup>12</sup>. To minimize energy consumption per transmission, most of the nodes should be within a single hop transmission to a coordinator (cluster head) node. On the other hand, fault-tolerance requirements assume ability of the nodes to take on coordinator responsibilities and retransmit messages from other nodes. Cluster tree architecture inherits the best of start and mesh networks in this respect. WISAN coordinator (Fig. 3) controls a single cluster of the network. Number of nodes in cluster depends on the bandwidth requirement of the nodes.

The protocol stack provides the following essential capabilities:

- command interface for sensor node configuration
- data interface for sending/receiving data
- global time synchronization between nodes in the network
- bandwidth scheduling for minimization of energy consumption and network latencies



Fig. 3. Front and rear view of a WISAN coordinator.



Command interface allows individual configuration of parameters controlling data acquisition, storage and transmission. Such parameters include sampling rate, ADC channels to be sampled, inclusion/exclusion of a temperature stamp to accompany the data, etc. Commands also control data transmission over the data interface, for example, total number of samples to be delivered to the coordinator. Command can be sent to an individual node in the network or broadcast to all nodes in cluster.

Global time synchronization is performed by sensor nodes adjusting to the clock on coordinator node. The coordinator node emits periodic beacons that are received by every node in the cluster. The node hardware captures the exact time stamp (in local time) of the arriving beacon. The difference between coordinator time (implied by the beacon) and local time is computed and local time is adjusted to match coordinator. The clock timer for active mode runs at 8 MHz frequency and beacons arrive with a period ranging from several milliseconds to several seconds. Pending future experiential results, we estimate that the maximum time difference between the nodes in the network should not exceed several microseconds.

Bandwidth scheduling creates a major impact on scalability of the network, latency of the data and energy consumption per node. Fig. 4 illustrates the bandwidth utilization in network with variable number of nodes transmitting constant bitrate (3.2 kbps) streams of data. Such a scenario is typical for a monitoring application (obtained on a simulation platform). As it can be seen from the illustration, the network can support a very limited number (8) of concurrently transmitting sensors. The reason is in the CSMA-CA medium access procedure adopted by IEEE802.15.4. The limited randomness in generating node's backoff period creates situation where multiple nodes transmit at the same time and collide with each other. Each packet lost due to a collision has to be retransmitted, resulting in higher latency and higher energy expenditure. Implementing TDMA scheduling virtually eliminates the collisions, allows the majority of nodes to transmit on a single attempt and allows for a significantly higher number of concurrently transmitting nodes (30).

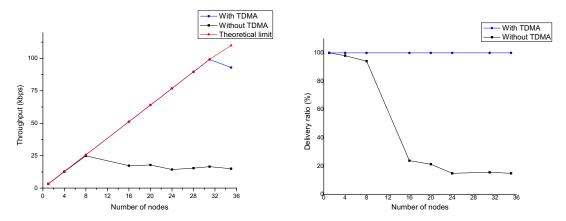


Fig. 4(a) Throughput and (b) Packet Delivery Ratio of the networks with and without using TDMA based scheduling as a function of increasing number of nodes of the network.

### 5. VALIDATION TESTS

WISAN sensor nodes have undergone extensive validation tests in the laboratory and field conditions. Some of these tests are still ongoing. The focus of testing was on accuracy of collected data, tolerance to environmental conditions and scalability.

• Effective Number Of Bits (ENOB) of ADC conversions: Our earlier work <sup>15</sup> describes experiments conducted on WISAN platform in order to establish ENOB of internal and external ADC converters. The nominal number of bits specified by the manufacturer can be a deceiving measure of accuracy and generally is not a valid way to specify

accuracy of acquired data. ENOB is computed from measured Signal-to-Noise Ratio and specifies the overall accuracy of the ADC transfer function.

The testing measured ENOB of a battery-powered system continuously transmitting sensor data to the coordinator nodes. Continuous transmission creates significant noise on the power lines due to current spikes created by the transceiver chip. As Table I shows, the accuracy of data acquisition is reduced compared to manufacturer specifications, with the best accuracy achieved by a Sigma-Delta ADC converter.

	Table I.	Summary	of ENOB	tests.
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ADC	Conversion principle	Nominal number of bits, bits	Manufacturer- specified ENOB at 100Hz, bits	Experimentally measured ENOB at 100Hz, bits	Maximum sampling rate, sps	Supply voltage, V
ADS1216	Sigma-Delta	24	≈20	16	780	2.7-3.3
ADS8325	SAR	16	13.8	12	100,000	2.7-3.6
MSP430F149	SAR	12	-	11.5	200,000	2.7-3.3

• Testing in environmental chamber. Practical applications of WISAN would require tolerance to extended temperature range that can range from very low temperatures to very high temperatures. A WISAN sensor node was tested under extreme environmental conditions from -35°C to +80°C (-31°F to 176°F) in the environmental chamber kindly offered by the New York State Department of Transportation and reliably operated in this temperature range <sup>16</sup>.

Fig. 5 shows a sensor box in the environmental chamber. A thermocouple controlled the rate of temperature change and absolute temperature inside the chamber. During experiments, the chamber was driven to the target temperature at the maximum possible rate. The environmental chamber tests have shown reliable operation of WISAN at extended range of temperatures.



Fig. 5. WISAN sensor box in environmental chamber.

• Single sensor installation on RT-11 bridge in Potsdam, NY. One of the goals of the test was to establish environmental stability of WISAN sensor nodes in real life environmental conditions.

Fig. 6 shows the internal content of a sensor box. Fig. 7 shows a sensor box installed on bridge girder close to a midspan position. The sensor node spends majority of the time in sleep mode with only the real-time clock timer running to keep track of the time and wake the processor up for data sampling. The average power consumption of the sensor node is comparable with the self-discharge current of the batteries. Ultra-low power consumption would allow this sensor operate for years on a single set of batteries.

The internal temperature sensor of MSP430 microcontroller acquires a single reading every 64 seconds, averages 16 readings and stores inside a ring buffer in microcontroller's RAM along with the time stamps. The content of the ring buffer can be retrieved wirelessly on demand.

Extraction of the data is performed in an energy-efficient manner, where the node's radio is kept powered down most of the time. Since the data can be extracted at an arbitrary time, the node has no predefined knowledge about upcoming data exchange. Idle listening would drain the battery very quickly, so would blind transmissions. To minimize energy consumption, the sensor node performs a discovery procedure every 2 minutes. During discovery procedure, the node sends out a short ping packet and waits for an acknowledgement from the coordinator. If

coordinator is not present, the acknowledgement will not be generated and the sensor node will go back into sleep mode. If a transmission is acknowledged, the sensor node understands it as a signal to transmit the content of the ring buffer. The coordinator node receives the data and stores it on an SD storage card that can later be read on a personal computer.





Fig. 6. Internal view of a sensor box

Fig. 7. Sensor installation on RT-11 bridge.

Nature fully cooperated with the intent to subject the sensor node to a wide range of extreme temperatures. Fig. 8 shows the girder temperatures during the first three weeks of January. The temperature readings normally lag the weather due to huge thermal mass of the bridge and smooth out the temperature gradients, but accurately reflect stable ambient temperatures. Result of this experiment show reliable operation of WISAN nodes under significant

temperature gradients and low temperatures.

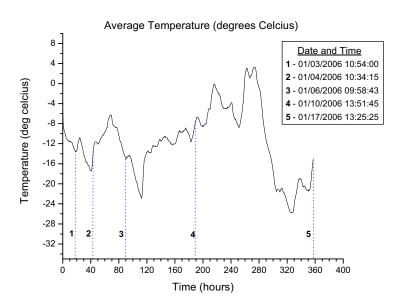


Fig. 8. Girder temperature measured by the node

Self-powered pressure sensor. This experiment pursued a demonstration of WISAN as an ultra-low power platform that is capable of operating on harvested energy. The demo unit is shown in Fig. 9. A motor with a counter balance weight creates the vibration that excites a piezoelectric bimorph (of course, in a real-life application vibration will come from a natural source). The output of the piezoelectric bimorph is connected to the rectifier/capacitor bank/regulator circuit that powers a WISAN sensor node. The resistive pressure sensor is built on an extension board and is connected to the WISAN node. The sensor reacts to the manually applied pressure created by applying force to the sensor pad. The resolution of sampled sensor data is reduced to 8

bits for minimization of network traffic and associated energy expenditures. The node transmits the sensor data through a simplified IEEE802.15.4 MAC protocol and delivers the data to a coordinator node that displays the real-time waveform on a graphical LCD display and forwards the data via USB to a personal computer with the Labview front end for displaying and storing of the data. A short video demonstration of the self-powered sensor is available for download on www.ambiosystems.com.

The goal of building this demonstration system was to construct a device which is capable of operating from energy harvested from a vibrating energy source and delivering a steady stream of low-latency sensor data to the main computer. The demo unit acquires pressure data at 30Hz frequency and delivers the data every 3s to a graphical LCD and a PC connected via USB interface. This test shows that a self-powered WISAN sensor is capable of acquiring data at a fairly high sampling frequency and delivers the data to a personal computer.

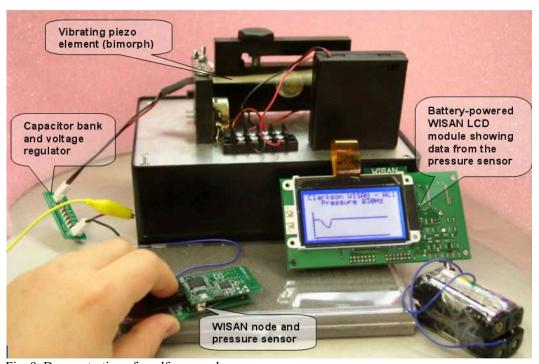


Fig. 9. Demonstration of a self-powered sensor.

 A small network test on RT-11 bridge in Potsdam, NY. The tasks related to WISAN platform testing included testing of the chosen MEMS acceleration sensors and signal conditioning circuitry and testing of the time synchronization between sensor nodes.

Each sensor box (Fig. 10) consisted of a low-noise MEMS accelerometer, gain and offset correction circuitry, 4th order anti-aliasing filter with cutoff frequency of 30Hz and a WISAN sensor node. The whole assembly was packaged into an ABS plastic box. The battery pack was attached to the lid. A key switch allowed turning the power on/off without opening the box. The box is mounted to the bridge by the means of Neodymium Iron Boron (NdFeB) magnets.

Data from the sensors were wirelessly sent to the coordinator modules attached to a notebook PC via USB interface. The Labview interface allowed visualization of the sensor data and storage on the hard drive. Responsibilities of the coordinator node include control over the network, including ensuring reliable data delivery, issuing command to the sensor nodes and receiving data from the sensor nodes, and maintaining global time synchronization in the nodes. The coordinator node was powered off the USB interface.

Acquisition of vibration data was performed in two basic configurations:

- Test 1. Four sensors were placed on girder with approximately 12 ft between the sensors (Fig. 10). The closest to the support is identified by number 1000 in the following figures. The sensor closest to the mid span of the girder had the number 1003.
- Test 2. Two sensors were placed side-by-side at two different locations on the girder. Sensors 1003 and 1002 were placed together at the previous location of sensor 1002; sensors 1000 and 1001 were placed at the previous location of sensor 1001.

After initial installation of sensors the data collection procedure consisted of the following steps:

- o the coordinator node and the sensors were powered up
- o the offset compensation circuit on the sensors was adjusted to produce a steady state reading around the midrange, compensating for the slanted surface of the girder's flange.
- the sensors were configured via the wireless interface to acquired data at 100Hz, ADC turned on, sensor turned on, time synchronized between the nodes
- o vibration data was acquired several times for the period of time between 1 and 5 minutes

The following figures illustrate the data from Test 1. Fig. 11 shows the time series from each of the sensors. As it can be seen from Fig. 10, the location at support is experiencing little excitation by passing traffic and amplitude of vibration decays approaching the supports. Fig. 12 shows frequency spectra of the girder vibration. All sensors except the support-mounted device show the same major harmonics reflecting the natural frequencies of the bridge.

The goal of the second test was to prove repeatability of sensor readings acquired by multiple sensors at the same location, i.e. verification of global time synchronization between sensors. Each

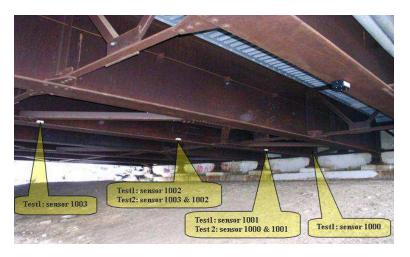


Fig. 10. WISAN installations on RT11 bridge.

sensor node is an independent device sending data to the coordinator module. Global time synchronization is essential for reliable operation of many damage detection algorithms. Fig. 13 shows the time series data acquired for 35 seconds from sensors 1002 and 1003 placed at the same location. Visually the both sensors are providing virtually identical data. To further exemplify the time synchronization of data, Fig. 14 shows a short piece of the waveform. Except for a small offset which is created by minor difference in sensor inclination relative to gravity, two waveforms are identical and track one another sample-by-sample. Fig. 15 illustrates identical frequency spectra produced by both sensors.

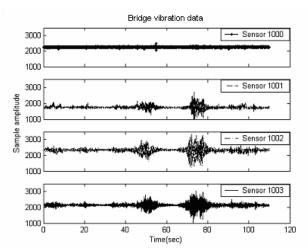


Fig 11. Time series acquired from WISAN sensors.

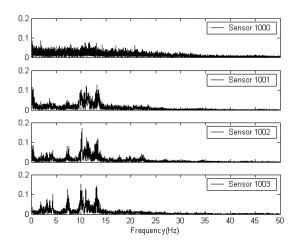
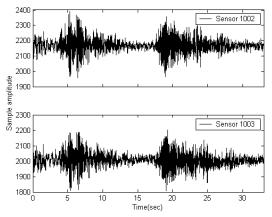


Fig. 12. Frequency spectra.



Data

4000 | Sensor 1002 | Sensor 1003

3500 | Sensor 1003

1500 | Sensor 1003

1500 | Sensor 1003

Fig. 13. Time series data from two sensors.

Fig. 14. Zoomed in time series from two sensors.

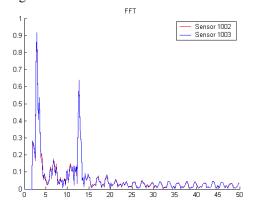


Fig. 15. Frequency spectra from two sensors sharing the same location.

#### 6. CONCLUSIONS

WISAN platform is based on a set of requirements that we see as essential for autonomous, unattended monitoring applications. WISAN hardware and software aim at satisfying these requirements to the fullest. WISAN sensor nodes provide an ultra-low-power platform for structural health monitoring involving scales from a single node to large networks.

Scalability of WISAN installations is provided through hierarchical cluster-tree network architecture and energy-efficient bandwidth scheduling algorithms that also improves overall latency of the data, and allows for real-time stream of synchronized data. Special consideration is given to reliable and secure operation in densely populated ISM frequency band. Autonomous operation of the monitoring system is provisioned through extremely low power consumption in operational and standby modes of operation. Finally, a capability to work with heterogeneous arrays of sensors and actuators is ensured by a variety of analog and digital interfaces.

Functionality of WISAN nodes is being tested on real-life applications in real environmental conditions. So far the test have shown reliable operation of WISAN nodes in extreme range of temperatures and temperature gradients; numerically quantified the accuracy of data acquisition provided by the sensor nodes; proved that WISAN nodes can be utilized in combination with energy harvesting devices and operate on very low energy levels provided by those devices; and global time synchronization allows for wired-like behavior in large networks.

#### **ACKNOWLEDGEMENTS**

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