

Network Architecture Design of an Agile Sensing System with Sandwich Wireless Sensor Nodes

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ABSTRACT

Wireless sensor network (WSN) is recently emerged as a powerful tool in the structural health monitoring (SHM). Due to the limitations of wireless channel capacity and the heavy data traffic, the control on the network is usually not real time. On the other hand, many SHM applications require quick response when unexpected events, such as earthquake, happen. Realizing the need to have an agile monitoring system, an approach, called sandwich node, was proposed. Sandwich is a design of complex sensor node where two Imote2 nodes are connected with each other to enhance the capabilities of the sensing units. The extra channel and processing power, added into the nodes, enable agile responses of the sensing network, particularly in interrupting the network and altering the undergoing tasks for burst events. This paper presents the design of a testbed for examination of the performance of wireless sandwich nodes in a network. The designed elements of the network are the software architecture of remote and local nodes, and the triggering strategies for coordinating the sensing units. The performance of the designed network is evaluated through its implementation in a monitoring test in the laboratory. For both original Imote2 and the sandwich node, the response time is estimated. The results show that the sandwich node is an efficient solution to the collision issue in existing interrupt approaches and the latency in dense wireless sensor networks.

Keywords: Wireless Sensor Network; Structural Health Monitoring; Sandwich Node

1. INTRODUCTION

Structural Health Monitoring (SHM) is essential in maintaining the safety and functionality of infrastructure, as public assets. The fundamental building block of SHM systems is its sensing network and therefore, the performance of the sensing network has a direct impact on the performance of the whole monitoring system. One of the most effective improvements, introduced to the SHM in the last two decades, is deployment of wireless technology for data communication in networks. Deploying Wireless Sensor Networks (WSNs) in SHM showed inherent potential in improving the monitoring techniques in terms of cost and deployment. Due to the advantages of WSNs, researchers developed different WSN platforms and deployed in SHM systems [1] to [5]. While WSN makes the deployment of SHM significantly more convenient, there are a few challenges such as prohibitive power consumption, limited communication bandwidth and latency of network in their real-life application. Since last decade, many researches have been conducting studies, addressing these challenges [6] to [8], but the current state of WSN still has some basic limitations for SHM.

One of the limitations in deploying WSNs is the lack of agility of the network in responding to the sudden events (e.g. Earthquakes). A simple classification of sensor networks, based on the mode of functionality, divides them into two classes: (i) Proactive Networks, and (ii) Reactive Networks. In the proactive networks the sensors are pre-programmed to periodically turn on, measure the quantity of interest and transmit the data (either processed or raw) to the base station. However, in the reactive scheme, the sensor nodes are designed to react to any sudden and drastic changes in the network.

Literature shows deployments of WSN on large-scale structures which, despite frequent data collection periods, have failed capturing earthquake events [9]. The reason is simple: when the earthquake happened, the network was either asleep or transmitting data collected prior to the arrival of the event. Therefore, considering the importance of having a

sensor network capable of capturing sudden events like earthquake, the reactive network design is essential. While reactive scheme of sensing network is quite common in the traditional wired sensor networks, its implementation on wireless network designs is very challenging. This difficulty is mostly due to the limitations of wireless channel capacity and the heavy data traffic in communication.

An approach addressing the limited channel capacity is, so called, sandwich node, proposed by [10]. Sandwich is a design of a complex sensor unit where two Imote2 nodes are connected with each other to enhance the capabilities of the sensing units in terms of communication and processing power. The extra channel and processing power, added into the nodes, enable agile responses of the sensing network, particularly in altering the undergoing tasks for sudden events. Also, to have an agile network that is fully automated, a smart observer sensor is required which captures the events and takes the control of the network (e.g. interrupts the undergoing task, or wakes up the slept sensor units in the network, and makes them run the desire task). This goal can be achieved by programming a sensor for continues sensing, capturing events and declaring predetermined messages.

This paper presents the design of an agile network of wireless sensors which is controllable and automated, suited for monitoring of infrastructure with capability of timely capturing the event responses. A testbed is designed to evaluate the performance of the network architecture throughout experimental implementation. The designed elements of the network are the software architecture of remote and local nodes, and the triggering strategies for coordinating the sensing units. The performance of the designed network is evaluated through its implementation in a monitoring test in the laboratory.

2. NETWORK ARCHITECTURE DESIGN

2.1 Selected Processing and Sensing Boards of the Sandwich Node

The platform which is used as the processing board of this design is Imote2^[11], developed by Intel. This platform integrates low-power PXA271 XScale^[12] CPU which operates in a low-voltage and low-frequency mode and enables low-power operation. Two different low-power modes provided for operation of the processor are Sleep and deep sleep modes. The frequency of processor can be scaled from 13MHz to 416 MHz with dynamic voltage scaling, which enable optimizing the power consumption. Imote2 also integrates 256 kB SRAM, 32 MB SDRAM, and 32 MB of FLASH memory, which has distinguished this platform from other smart sensor platforms. The CC2420 IEEE 802.15.4 radio transceiver, from Texas Instruments, is deployed for communication purpose and supports a 250 kb/s data rate with 16 channels in the 2.4 GHz band. It should be noted that this communication throughput is the nominal rate of the transceiver and the real throughput also relies on other aspects of the network, such as data transmission routing and environmental conditions. A 2.4 GHz surface mount antenna is provided on the Imote2 platform together with an additional external antenna, Antenova Titanis 2.4 GHz Swivel SMA. Table 1 shows the general specifications of the Imote2 platform.

Table 1, Specifications of Imote2^[11] and LIS3L02AS4 on SHM-A^[13] Sensor Board

Imote2 Processing Board		LIS3L02AS4 Accelerometer	
Processor	Intel PXA271	Acceleration	±2 g
SRAM Memory	256 kB	Avg. Noise Floor (X&Y)	0.3 mg
Memory	32 MB (SDRAM/FLASH)	Avg. Noise Floor (Z)	0.7 mg
Power Consumption	44 mW at 13 MHz	Resolution	0.66 v/g
	570 mW at 416 MHz	Temperature Range	-40 to 85°C
Radio Frequency Band	2400.0 – 2483.5 MHz	Dimension	45×45 mm
Dimensions	36 mm×48 mm×9 mm		

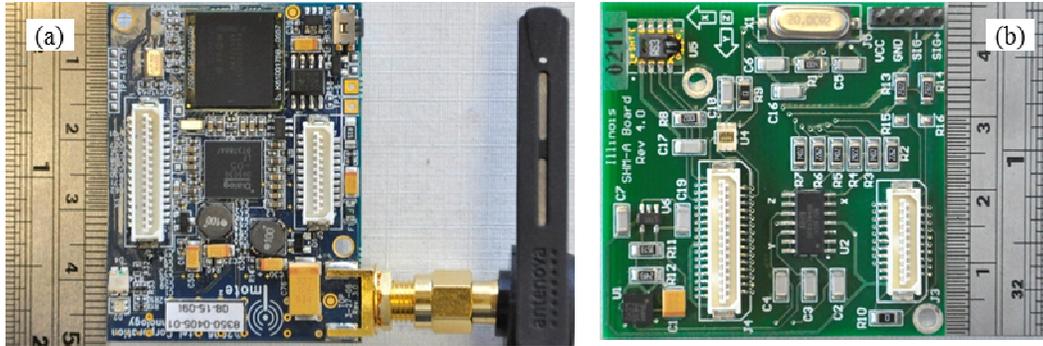


Figure 1, Imote2 processing board and SHM-A sensor board

For acceleration sensing, in this particular testbed, the SHM-A sensor board is selected. SHM-A^[12], developed at Smart Structures Technology Laboratory at the University of Illinois at Urbana-Champaign. The components of this sensor board are selected based on structural health monitoring applications. The LIS3L02AS4 analog accelerometer, manufactured by ST Microelectronics, is used for the SHM-A sensor board. LIS3L02AS4 is a tri-axial, low-cost, high-sensitivity analog accelerometer with $50 \mu\text{g}/\sqrt{\text{Hz}}$ noise density. Specifications of the accelerometer can be found in Table 1. Figure 1 (a) and (b) also show the hardware platform of the Imote2 and the SHM-A sensor board.

2.2 Sandwich Node Architecture

Sandwich-node is a design of wireless sensor unit which addresses the limitations of the previous generation of integrated sensing/communication/ processor devices that have been utilized in SHM applications [10]. The proposed unit consists of two processor/communication nodes, a sensor board and a single antenna, and can support the prioritization and interruption functionalities. The architecture design of the sandwich node is based on the criteria for a capable WSN for monitoring the response of an infrastructure to earthquake excitations. Figure 2 shows the proposed architecture of the sandwich node.

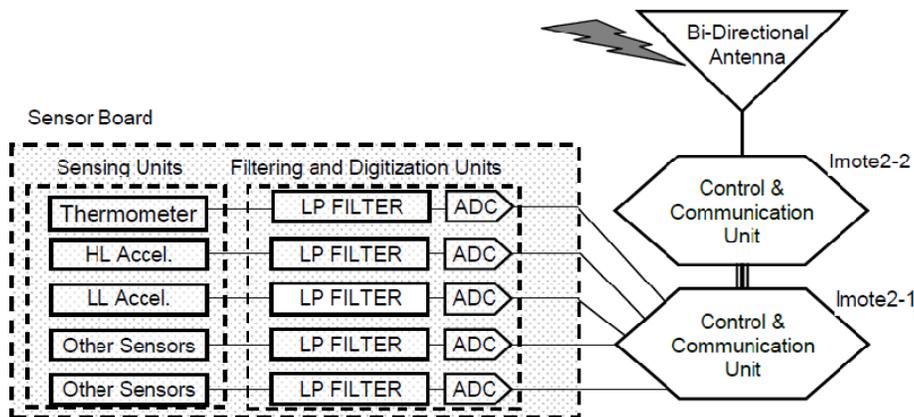


Figure 2, Architecture design of the proposed sandwich-node

The two processing units of the sandwich node share the responsibilities as follow: the first mote is dedicated to manage the control of the sensor board and perform on-board data processing if required (Imote2-1); the second mote is in communication with the first mote through the communication interface to exchange command and data. This mote (Imote2-2) is responsible for maintaining the time-synchronization within the node, communicating data and commands with the network and interpreting and relaying them to the first mote (Imote2-1). These dual control units help increase the computational capability of the node to perform more complicated analysis on the data, maintain alertness in the network by providing accurate time synchronization at each node, and provide accurate clock for fast sampling with small jitter [10].

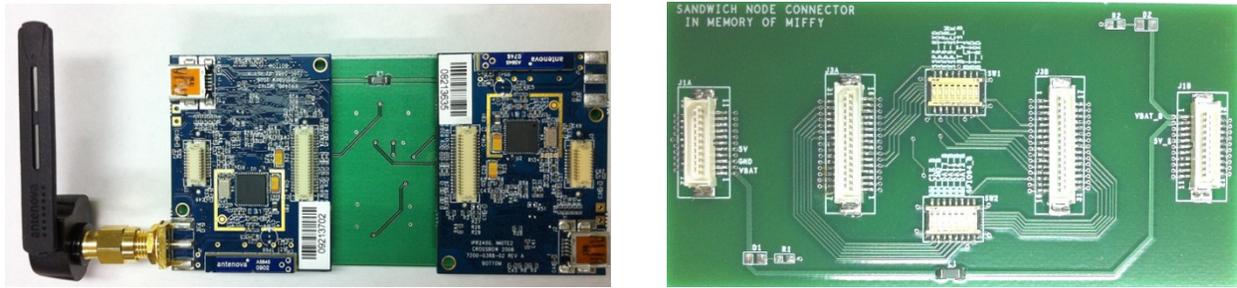


Figure 3, Sandwich node prototype connecting two Imote2s

For the communication between the two processing boards the available UART communication port is used (one serial peripheral interface and several GPIOs). Interfacing two Imote2 through a serial port is a commonly used method in processor interconnections. It allows a data bandwidth ranging from several kilobytes to several megabytes with a few physical connections. However, this method complicates the software design as it needs codes that implement the serial communication protocol and device drivers. On the other hand, interfacing two Imote2s with GPIO is a simpler approach both in hardware and software. In the design of the sandwich node prototype, the GPIO is used for interconnection. Figure 3 shows the prototype's photo with two connected Imote2s. To avoid interfere of signals in communications of the two processing units, their frequency bands of operations are selected to be different. With this structure and configuration, the sandwich node can respond to emergency events in real-time.

2.3 Smart Triggering Sensor

As mentioned earlier, having a reactive sensor network is essential in SHM systems, particularly those intended to operate for long term. One of the necessary components of such system is a sensor unit which alerts the network for sudden changes in their duties. This unit, called smart triggering sensor, is to be programmed to continuously measure the quantity of interest (e.g. acceleration) and, in case of occurrence of event (e.g. high amplitude of vibration due to wind or earthquake), broadcast a proper message. The proper alert message should include (i): an interrupt of any undergoing task such as communication or processing the data (except the sensing task when the sensing parameters are not subject to change), or an awakening message for the case that the network is in sleep mode, and (ii): run the sensing with pre-determined, desired parameters. Figure 4 schematically shows the described network with the triggering sensor.

Particular application of this sensor network architecture is in monitoring of structural systems subjected to earthquake events. To enable the triggering sensor to capture such events, it should be sensitive to amplitude of the vibrations. This type of triggering is common in programming of wired data acquisition systems (e.g. CR9000^[14] data acquisition system). For this network architecture also, similar triggering algorithms is adopted and programmed on the triggering node. It worth noting that capturing earthquake response is not the only response which is worthwhile for SHM, but in general, capturing any high amplitude response (e.g. response to high speed wind or excessive loads) provides more effective information and eventually more informative results. Therefore, the triggering sensor could be programmed for a general scenario which detects high amplitude vibrations (or other variables such as wind speed) and enables the network to capture the corresponding responses.

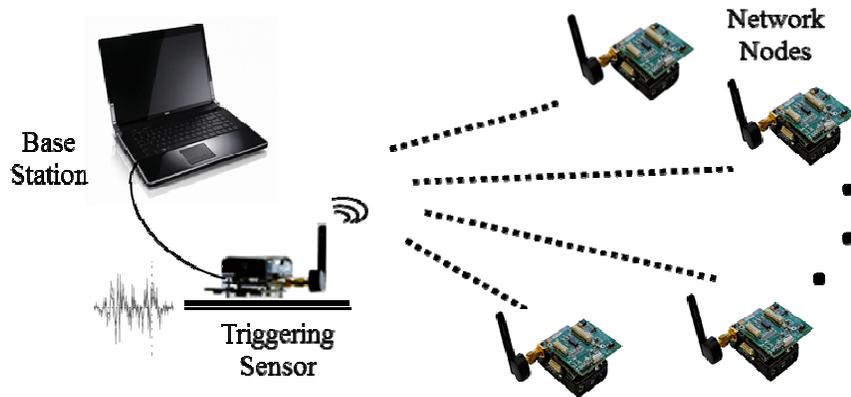


Figure 4, Sensing Network with Triggering Node, controlling the networks task

3. VALIDATION OF THE NETWORK PERFORMANCE

3.1 Testbed for Performance Evaluation

To validate the performance of the designed network architecture, a testbed structure is instrumented by the sensor network and a real-life scenario is simulated. The testbed structure is a three-dimensional still truss as can be seen in Figure 5. A network of wireless sensors with sandwich design is installed on the structure and a triggering node, apart from the sensing network, is mounted on a shaking table and detects the excessive vibrations, generated by the table.

Considering a long term monitoring scenario for the deployed network, different periodic tasks are assigned to the sensor units. The next section presents the performance evaluation of the sensing network during different as respond to the interrupt message of the triggering sensor.



Figure 5, The Testbed for evaluating the performance of network's response

3.2 Performance Evaluation, Results

Depending on the undergoing task, the network may have different response to the commands issued by the triggering node. To evaluate the performance of the network during different tasks, the delay in the response of the sensing network is measured as a function of task.

Two sets of experiments are conducted to demonstrate the performance of the sandwich nodes in comparison with the regular sensing units. The communication scenario in this experiment is shown in the Figure 6. Two nodes are: a regular

node running the remote sensing application, the other one include two sub-nodes: one slave Imote2 running the same remote sensing application, plus an extra Imote2, so called scout node, which keeps listening to the wireless channel. The two Imote2s of the sandwich node are connected using GPIO. When the experiment begins, an external node works as a base-station and sends out the remote sensing parameters and commands periodically. The two sensor nodes will run the remote sensing routine once they receive the commands. At the same time, a forth node will send out wireless signal (interruption), and thus, the pure remote sensing node will get the interruption through the wireless transceiver while the one on the sandwich node will receive a GPIO interruption instead.

The working status of the remote sensing is divided to four stages:

- i. The idle state: when the node is done with last data acquisition and not yet in the next one. In this stage we assume that all the devices and resources on the node are available.
- ii. The data acquisition stage: when the node is sensing or during the process of requesting sensor data. During this stage the wireless transceiver is available but the CPU may have high turn-around time.
- iii. The time synchronization stage: when the node is running the time synchronization algorithm which requires extensive time stamp exchanges. In this stage the wireless receiver is usually occupied.
- iv. The flash memory operation stage: when the node is done with the data collection and is in the process of writing the contents of the main memory into the flash memory for storage.
- v. The data transferring stage: This is the stage when the chunks of data are transferred from the remote node to the base station. The wireless transceiver is also heavily occupied during this period.

The time interval between two interruptions is randomized, so each stage of the remote sensing is expected to be interrupted with similar frequency.

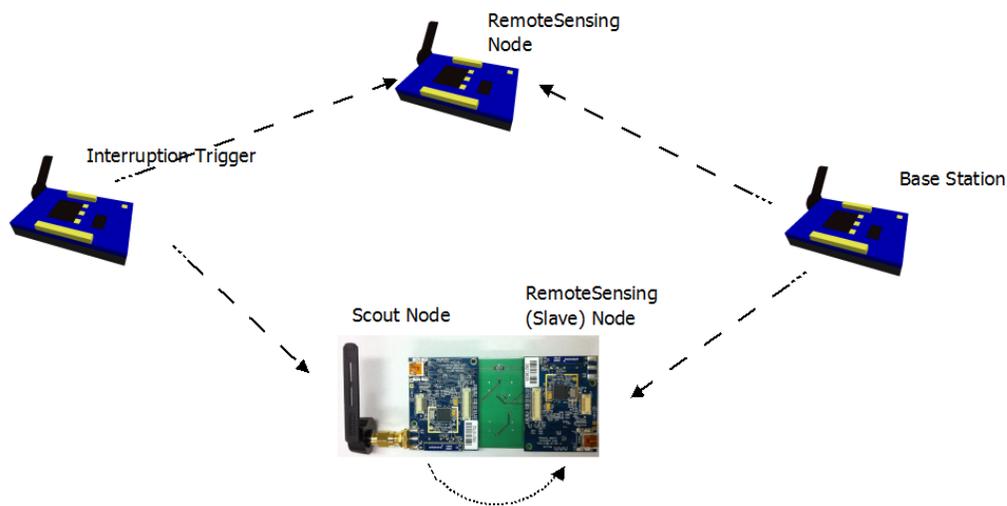


Figure 6. The experiment scenario for network interrupt

The observed delay is the time difference between the sending out time of the interrupt and the response time of the remote sensing nodes. 30 results are recorded for each stage and the average values are plotted in the Figure 7. From the results, it can be seen that when the wireless transceiver is less occupied, the sandwich node solution has similar performance with the one of the wireless signal (in the idle state, it is even a little bit worse). However, in the stage when the wireless channel is heavily used, such as the time synchronization and the data transmission, the time delay of traditional wireless interruption is higher, while the sandwich node still performs the same. This experiments show that the overall delay performance of the sandwich nodes is better than that of the original wireless interrupt mechanism.

The other advantage of using sandwich node is that the second Imote2 (scout node) is responsible for synchronizing the sensing network. This means that the synchronization can be performed frequently, disregard the undergoing task, and therefore, the network can start capturing the response to sudden events right after the message is received from triggering node. The capability of maintaining time-synchronization is in particular important when quick measurement of response is necessary (e.g. Earthquake response).

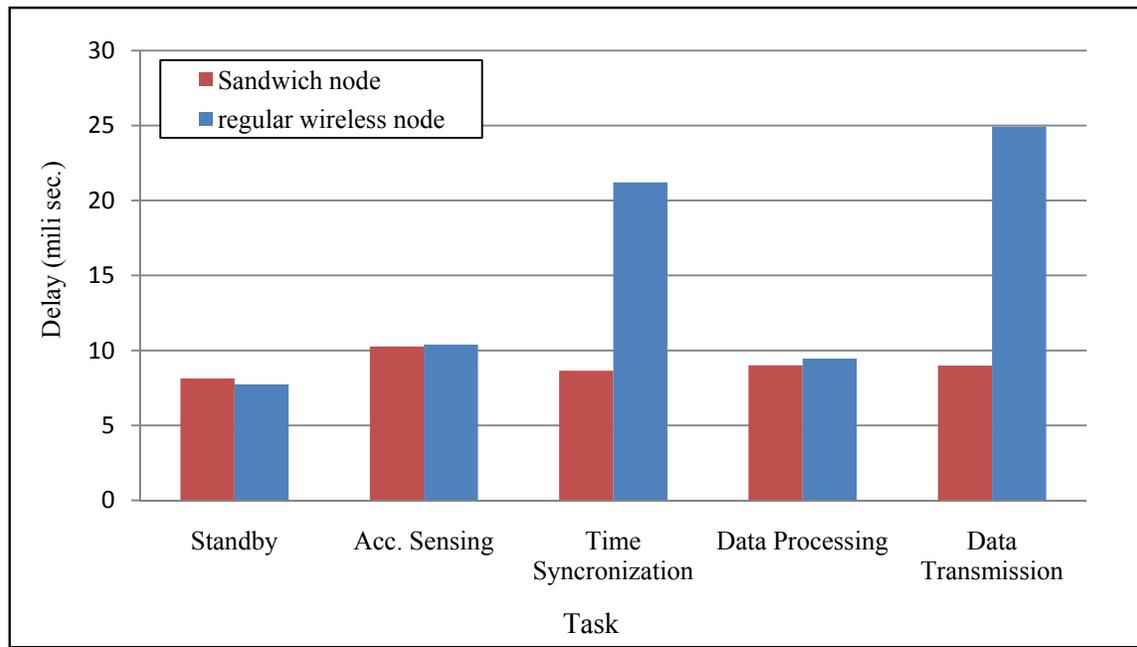


Figure 7. Time delay of different phases, comparison of sandwich node with the regular sensor

4. CONCLUSION

This paper presented the design of a testbed for evaluating the functionality and performance of wireless sandwich nodes in a network during sudden events. The software architecture of network consisted of simple sensing of remote sensors and a triggering strategy for coordinating the network, and in particular, interrupts the undergoing tasks. The performance of the network is evaluated through the implementation in a monitoring test in the laboratory. For both original Imote2 and the sandwich node, the response time is estimated. It is showed that by bridging two sensor nodes (sandwich node) using GPIO, the functionality is extended and the response performance is enhanced. The future work is to develop more applications to take advantages of the extra computing power and channel resource of the sandwich nodes.

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