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# RESEARCH AND DEVELOPMENT IN STRUCTURAL HEALTH MONITORING OF BRIDGES WITH A WIRELESS SENSOR NETWORK

Su Jian
Research Institute of Highway, the Ministry of Communication, China

Zhang Jinquan
Research Institute of Highway, the Ministry of Communication, China

Cai Shuri
Research Institute of Highway, the Ministry of Communication, China

Li Wanheng
Research Institute of Highway, the Ministry of Communication, China

Li Zhan
Research Institute of Highway, the Ministry of Communication, China

## Abstract

Structural health monitoring (SHM) is an active area of research devoted to systems that can autonomously and proactively assess the structural integrity of civil buildings. Structural monitoring systems using wireless sensors have the potential to serve as low-cost alternatives to commercially available cable-based monitoring systems. In this paper we discuss our deployment experiences and evaluate the performance of a multi-hop wireless data acquisition system for structural health monitoring (SHM) of bridges. Our experiments indicate that, with the latest sensor network hardware, our networks can reliably deliver time-synchronized vibration data across multiple hops with low latencies for sampling rates up to 350Hz. From findings from a field validation test, strong agreement is observed between the data collected by the wireless system and cable-based monitoring system.

## INTRODUCTION

Recent advances in sensing, data acquisition, computing, communication, data and information management have been made through increasing the application of structural health monitoring systems in bridges. Successful implementation and operation of structural health monitoring (SHM) on bridges have been reported worldwide. Traditionally, most existing SHM systems use wired data acquisition systems to collect structural vibration data from various locations in the structure (induced by ambient sources e.g., moving vehicles, winds) for analysis. Installing a large-scale wired data acquisition system may sometimes take several weeks and may often turn out to be prohibitively expensive. A wireless sensor network-based data acquisition system promises enormous benefits such as ease and flexibility of deployment in addition to low maintenance and deployment costs.

Broadly speaking, a SHM system attempts to use different sensors to localize damage and detect its performance through structural response. Recent technological advances promise the ability to monitor large civil structures with low-cost wireless sensors that can continuously monitor a building's structural health, but researchers face several obstacles to achieve this goal, including high data-rate, data- reliability, and time-synchronization requirements. Given the challenges involved, we prototyped a set of hardware systems and wireless network protocol, and experimented with them on realistic structures. A wireless sensor network-based data acquisition system delivers time-synchronized structural-response data reliably from several locations over multiple hops to a monitoring center was provided and developed. It supports flexible sensor-network deployments of up to several tens of wireless nodes and avoids the high cabling, installation, and maintenance costs incurred by traditional wired data-acquisition systems. It uses a three-layer hierarchy, with resource-constrained sensing nodes in the lowest layer, gateway nodes in the second layer and a monitoring center at highest layer; theoretically, it can scale to hundreds of nodes. The wireless sensing unit can acquire data and reliably transmit it across the multi-hop gateway node to a monitoring center. In this implementation, we can sample vibrations at 300Hz and store the data locally. Memory on the sensor node allows for sampling up to 30 minutes or real time transport but support less sensing nodes. After sampling, the stored data is transmitted reliably over a multi-hop sensor network. The system also provides time synchronization. Authors have deployed this system on a small-scaled model of a building. This article summarizes the design of the SHM systems and discusses their performance.

## WIRELESS SENSOR NETWORK ARCHITECTURE

In this section, we summarize the design of our SHM system for completeness. Fig. 1 shows the architecture of the SHM system. The entire SHM system includes a monitor centre, some gateway nodes and other wireless sensing nodes. Using the gateway nodes and wireless transceiver, the monitoring center can communicate with the wireless sensing nodes that are distributed throughout the bridge structure. The system can support tens of gateway nodes and each gateway node also can accommodate tens of sensing wireless nodes placed at various locations on a large structure for a real time and reliable data transmit. The sensing nodes collect the time-synchronized data and transmit to the monitoring centre with the gateway nodes. Sensing nodes can support strain sensors, accelerator displacement sensors and so on. In this paper, we focus on the accelerator.

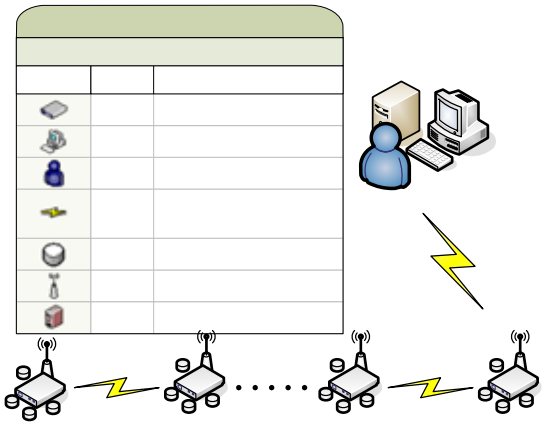

Figure 1. Example of wireless sensor networks

Each sensing node measures structural vibrations with the help of data acquisition (Fig. 2) specifically designed for high quality low-power vibration sensing (dynamic range of ±2 g, low noise characteristics with 24-bits/sample, 0.05-2,000 Hz sampling rate with programmable anti-aliasing filter), for the real time monitoring, the system can offer 300Hz sampling rate. This is suitable for SHM applications. A monitoring center provides the data processing, assessing and analysis.

In the system, this wireless network protocol comprises two essential components: reliable transfer of vibration data to the monitoring center; time-synchronization of samples generated across various sensor nodes within 0.5 millisecond. At every specific interval the monitoring centre broadcasts synchronous message and sensing nodes adjust the clock of data acquisition. A sensing node can be seamlessly removed or added in a working condition deployment by placing a new node and turning it off/on.

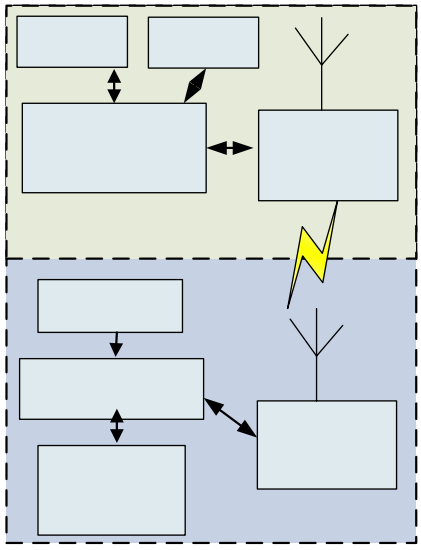


Figure 2. WSN node architecture.

Fig. 1 also shows the constitution of the WSN networks. The system uses a three-layer network hierarchy, with resource-constrained sensing nodes in the lowest layer, gateway nodes in the second layer and a monitoring center at highest layer. Fig. 2 shows the components of WSN hardware: sensing node and gateway node hardware. Both contain a micro controller unit and wireless transceiver. The micro controller unit is responsible for executing different embedded instructions from the monitoring centre and itself. A low-cost 8-bit microcontroller (Atmel ATmega128) is selected as the principle component. The key criterion for this selection is to balance the power consumption and cost of the microcontroller versus the computation power needed by software applications. Running at 16MHz, the ATmega128 consumes about 15mA when it is active.

Micro controller unit (CPU) is the kernel of node hardware. In this place, we use the ATmega8L and ATmega128L chip of Atmel Corporation for the micro controller unit. ATmega8L is applied in sensing node and ATmega128L is taken in gateway node. The wireless transceiver takes NRF2401 of NORDIC Semiconductor.

Figure 3. WSN gateway node hardware.

**Microcontroller Unit Characteristics**

Fig.3 shows our gateway node hardware. The ATmega128 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. It provides the following features: 128K bytes of In-System Programmable Flash with Read-While-Write capabilities, 4K bytes EEPROM, 4K bytes SRAM, 53 general purpose I/O lines, 32 general purpose working registers, Real Time Counter (RTC), four flexible Timer/Counters with compare modes and PWM, 2 USARTs, a byte oriented Two-wire Serial Interface, an 8-channel, 10-bit ADC with optional differential input stage with programmable gain, programmable Watchdog Timer with Internal Oscillator, an SPI serial port, IEEE std. 1149.1 compliant JTAG test interface, also used for accessing the On-chip Debug system and programming and six software selectable power saving modes. For ATmega8L, it has a similar function compared to the ATmega128L, the main difference is the ATmega8L contains less numbers than the ATmega128L for the same function.

**Wireless Transceiver Characteristics**

Fig.4 shows our nRF2401 wireless communication board. nRF2401 is a single-chip radio transceiver for the world wide 2.4 - 2.5 GHz ISM band. The transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a crystal oscillator and a modulator. Output power and frequency channels are easily programmable by use of the 3-wire serial interface. Current consumption is very low, only 10.5mA at an output power of -5dBm and 18mA in receive mode. Built-in Power Down modes make power saving easily realizable.

Figure 4. nRF2401 wireless communication board.

## SYNCHRONIZATION OF SYSTEM

The SHM application places very stringent requirements on wireless sensing software. The monitoring center with gateway nodes and wireless sensing nodes is integrated by communication software. The design of software should include three parts: a monitoring center program for central PC, a network communication program for gateway nodes, and a client program for sensor units. The complex signal-processing results in many SHM applications unable to tolerate data loss, thus reliable transmission of sensor data is an absolute requirement. This poses significant challenges for WSNs: their low-power wireless transceiver often deployed in atrocious radio environments, sometimes present data loss rates of 30 percent. Moreover, SHM signal-processing techniques temporally correlate data from multiple sensors. If the clocks on these sensors aren't synchronized, phase errors will adversely affect the data analysis. This is particularly true of damage localization algorithms that attempt to infer differences in mode shapes, which require clock synchronization within millisecond.

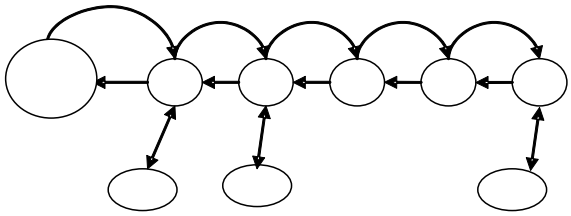

Figure 5. Time synchronization between 2 sensing nodes.

We evaluated the time synchronization performance with WSN deployed in the vibration test as shown in Figure 5. Nodes 1, 2 and 5 comprised the wireless sensor nodes in the network. Node 1 was connected to the monitoring centre (a PC) via a serial port. Accelerometers were connected to the sensing node. All sensing nodes were configured to sample at 250Hz. A data oscilloscope was used to measure the data sample pulse. As show in Fig.6(a), 10 microseconds clock difference was introduced between sensing nodes 6 and 7. Between 6 and 8 sensing nodes, they produced 25 microseconds clock difference. According to the results of test, we can deduce that the size of the clock difference is related to the number of gateway node. The larger the clock difference, the larger number of gateway nodes. For 0.5 millisecond requirement of time synchronization with hundreds sensing nodes, this WSNs synchronization design can meet the stringent application of SHM vibration test.

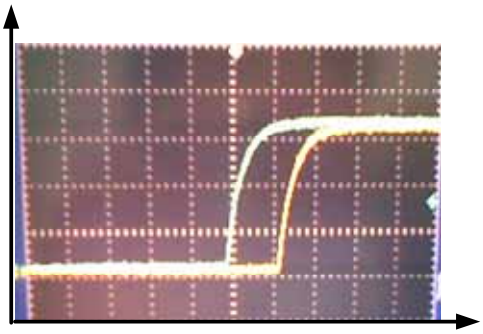


Figure 6.(a) Clock difference between 9 and 10 sensing nodes.

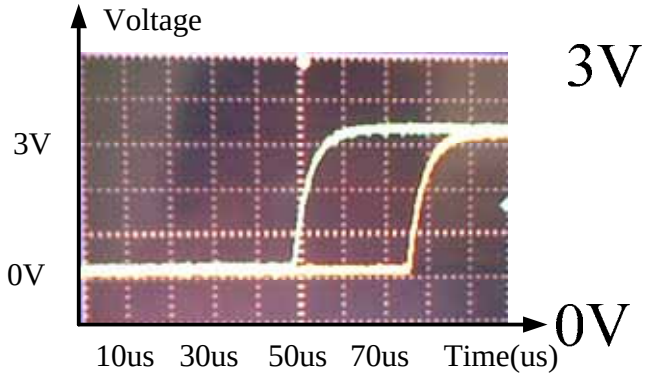


Figure 6.(b) Clock difference between 9 and 11 sensing nodes sensing nodes.

## PERFORMANCE TEST

891 accelerometers were used with both the cabled and the wireless systems for the vibration test. Sensing node modules are also used for filtering noise, amplifying and shifting signals. Sampling frequencies for the cable-based system and the wireless system are 250 Hz. Using the ambient excitation, Fig. 7 shows the time history data collected by the cable-based and wireless monitoring systems with ambient vibration. The difference between the two data sets can be mainly attributed to three sources: 1) the collected data weren't clock synchronized by the two systems; 2) the performance of signal conditioning modules are difference between the wireless system and cabled system; 3) the wired and wireless accelerometer locations are not exactly adjacent to each other.

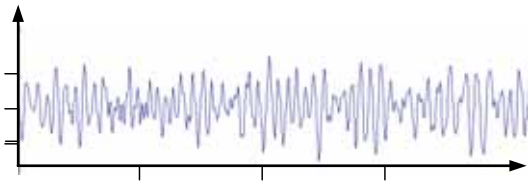

Figure 7.(a) wired.

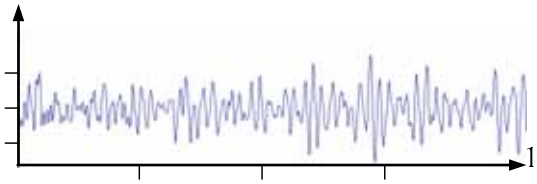

Figure 7.(b) wireless.

But a close match is observed in Fig.8, it shows the Fourier spectrum results determined from the time history data. In this place, the amplitude of wired conditioning module is ten times the wireless conditioning module. It can be seen that both results are in good agreement for the lowest resonant frequency. The frequency spectrum follows a similar trend. Strong agreement between the two sets of FFT results validates the computational accuracy of the wireless sensing units.

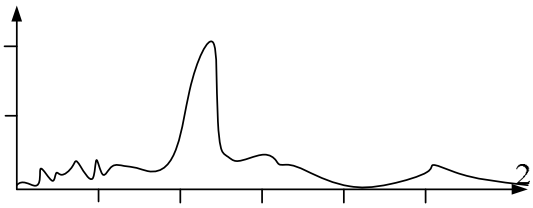

Figure 8.(a) wired.

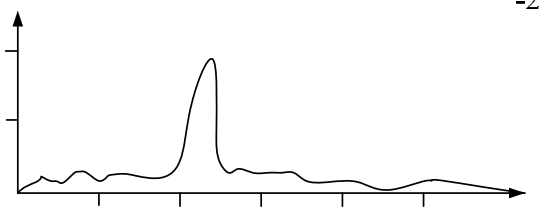

Figure 8.(b) wireless.

## CONCLUSION AND DISCUSSION

Many forces are drawing researchers as well as manufacturers to wireless technologies. The explosive growth of wireless communications has driven the cost of radio devices down and the quality up. With the ability to reduce installation costs, add flexibility, and ease deployment and maintenance hassles, the attractiveness of wireless technologies needs little reinforcement. Recently there has been a whole slew of research dedicated to wireless mesh networking. Behind this are some of the unique features of wireless mesh networks such as cost effectiveness, extended coverage, fault tolerance, load balancing, self-configuring, self-healing, and relatively smaller upfront investment.

In this paper we discussed deployment experiences and evaluated the performance of a multi-hop wireless data acquisition system for structural health monitoring (SHM) on bridges. Our experiments indicate that, with the latest sensor network hardware, our networks can reliably and in real time, deliver time-synchronized vibration data across multiple hops with low latencies for sampling rates up to 350Hz. Robust software and hardware designs enable low-cost and reliable data collections and interrogation between monitoring centre and wireless sensing units. With findings from a field validation test, strong agreement is observed by the wired and wireless monitoring systems.

## ACKNOWLEDGEMENT

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