TR 611

WIRELESS SENSOR NETWORKS FOR INFRASTRUCTURE MONITORING

FINAL REPORT

Submitted to:

Iowa Department of Transportation
Iowa Highway Research Board
800 Lincoln Way
Ames, Iowa, 50010

Submitted by:

Dr. M.D. Salim (PI)
Dr. Jin Zhu (Co-PI)
Department of Industrial Technology
College of Natural Science
University of Northern Iowa
Cedar Falls, IA 50614

October 2010

Disclaimer Notice

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the sponsors.

The sponsors assume no liability for the contents or use of the information contained in this document. This report does not constitute a standard, specification, or regulation. The sponsors do not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objectives of the document.

Iowa Department of Transportation Statement of Non-Discrimination

Federal and state laws prohibit employment and/or public accommodation discrimination on the basis of age, color, creed, disability, gender identity, national origin, pregnancy, race, religion, sex, sexual orientation or veteran's status. If you believe you have been discriminated against, please contact the Iowa Civil Rights Commission at 800-457-4416 or Iowa Department of Transportation's affirmative action officer. If you need accommodations because of a disability to access the Iowa Department of Transportation's services, contact the agency's affirmative action officer at 800-262-0003.

The University of Northern Iowa Statement of Non-Discrimination

No person shall be excluded from participation in, be denied the benefits of, or be subjected to discrimination in employment, any educational program, or any activity of the University, on the basis of age, color, creed, disability, gender identity, national origin, race, religion, sex, sexual orientation, veteran status, or on any other basis protected by federal and/or state law.

The University of Northern Iowa seeks to prohibit discrimination and to promote affirmative action in its educational and employment policies and practices. For additional information, contact the Office of Compliance and Equity Management, 117 Gilchrist Hall, UNI, (319) 273-2846, or visit www.uni.edu/equity.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
IHRB Project TR-611			
4. Title and Subtitle **TR-611 Wireless Sensor Networks for Infrastructure Monitoring**		**5. Report Date** October 2010 **6. Performing Organization Code**	
7. Author(s) M.D. Salim and Jin Zhu		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Department of Industrial Technology University of Northern Iowa Cedar Falls, IA, 50614		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**	
12. Sponsoring Organization Name and Address Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**	
15. Supplementary Notes Visit www.iowadot.gov/operationsresearch/reports.aspx for more information on this project.			

16. Abstract

A good system of preventive bridge maintenance enhances the ability of engineers to manage and monitor bridge conditions, and take proper action at the right time. Traditionally infrastructure inspection is performed via infrequent periodical visual inspection in the field. Wireless sensor technology provides an alternative cost-effective approach for constant monitoring of infrastructures. Scientific data-acquisition systems make reliable structural measurements, even in inaccessible and harsh environments by using wireless sensors. With advances in sensor technology and availability of low cost integrated circuits, a wireless monitoring sensor network has been considered to be the new generation technology for structural health monitoring.

The main goal of this project was to implement a wireless sensor network for monitoring the behavior and integrity of highway bridges. At the core of the system is a low-cost, low power wireless strain sensor node whose hardware design is optimized for structural monitoring applications. The key components of the systems are the control unit, sensors, software and communication capability. The extensive information developed for each of these areas has been used to design the system. The performance and reliability of the proposed wireless monitoring system is validated on a 34 feet span composite beam in slab bridge in Black Hawk County, Iowa. The micro strain data is successfully extracted from output-only response collected by the wireless monitoring system. The energy efficiency of the system was investigated to estimate the battery lifetime of the wireless sensor nodes. This report also documents system design, the method used for data acquisition, and system validation and field testing. Recommendations on further implementation of wireless sensor networks for long term monitoring are provided.

17. Key Words		**18. Distribution Statement**	
Wireless sensor networks, Infrastructure monitoring		No restrictions.	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	40	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Executive Summary

A good system of preventive bridge maintenance enhances the ability of engineers to manage and monitor bridge conditions, and take proper action at the right time. Structural health monitoring is a routine maintenance to structural elements such as highway overpasses, bridges and roads. Traditionally infrastructure inspection is performed via infrequent periodical visual inspection in the field. Wireless sensor technology provides an alternative cost-effective approach for continuous monitoring of infrastructures. Scientific data-acquisition systems make reliable structural measurements, even in inaccessible and harsh environments by using wireless sensors. With advances in sensor technology and availability of low cost integrated circuits, a wireless monitoring sensor network has been considered to be the new generation technology for structural health monitoring.

The main goal of this project was to implement a wireless sensor network for monitoring the behavior and integrity of highway bridges. At the core of the system is a low-cost, low power wireless strain sensor node whose hardware design is optimized for structural monitoring applications. The key components of the systems are the control unit, sensors, software and communication capability. The extensive information developed for each of these areas has been used to design the system. The performance and reliability of the proposed wireless monitoring system is validated on a 34 feet span composite beam in slab bridge in Black Hawk County, Iowa. The micro strain data is successfully extracted from output-only response collected by the wireless monitoring system. The energy efficiency of the system was investigated to estimate the battery lifetime of the wireless sensor nodes. This report also documents system design, the method used for data acquisition, and system validation and field testing. Recommendations on further implementation of wireless sensor networks for long term monitoring are provided.

Wireless Sensor Networks for Infrastructure Monitoring

Final Report

IHRB Project TR-611

Investigators

M.D. Salim (PI)
Professor, Construction Management
University of Northern Iowa

Jin Zhu (Co-PI)
Assistant Professor, Electrical Engineering Technology
University of Northern Iowa

Research Assistants
Pratiksha Holavannur and Souhail Saad
University of Northern Iowa
Department of Industrial Technology

Sponsored by

The Iowa Highway Research Board
The Iowa Department of Transportation
Research and Technology Bureau
800 Lincoln Way, Ames, Iowa 50010

October 2010

Acknowledgements

The authors would like to thank the Iowa Highway Research Board (IHRB), and Iowa Department of Transportation (IDOT) for sponsoring this research. The authors are grateful to the Technical Advisory Committee (TAC) members for their thoughtful discussions and input. The authors are also grateful to Blackhawk County engineers Catherine Nicholas and Nick Amelon, and bridge engineer (Retd.) Thomas Schoellen for making arrangement of live load tests on a county bridge. The authors would also like to acknowledge the administrative support of the Department of Industrial Technology at the University of Northern Iowa.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 Background and motivation

According to the data from Federal Highway Administration, over 23% of all bridges are deficient nationally as of August 2009 (FHWA, 2009). For the State of Iowa the deficient rate is 26.9%, including 5153 bridges that are structurally deficient and 1320 bridges that are functionally obsolete in 2009. Traditionally infrastructure inspection is performed via infrequent periodic visual inspection in the field. Most mandated bridge inspections are conducted by state workers who visually examine structures or perform hands-on tests. Typically, a public works employee is assigned the task of monitoring the condition of bridges in a city or country. During winter time, the bridges are heavily iced, and the ground surrounding the bridges' foundations is a mixture of treacherous ice and mud. The employee drives to each bridge, gets out of his truck, and makes his way to the foundations of the bridge. After making as many observations as possible, he drives to the next bridge and starts over.

This traditional way of infrastructure inspection may not be efficient due to limited inspection time, infrequent visit, and human mistakes. Improved inspection and monitoring methods are critical to prevent the loss of human lives and property due to accidents. The disaster caused by the collapse of the Minneapolis I-35 Bridge has pointed to the needs for better technologies to inspect and monitor bridges. There has been a growing interest in applying wireless sensing technology to structure and infrastructure monitoring. Networking the sensors to empower them with the ability to coordinate on a larger sensing task will revolutionize information gathering and processing in many situations. Distributed networks of sensors can greatly improve the infrastructure monitoring. Wireless sensor networks have drawn great attention recently because of its advantages and numerous potential applications. Wireless data communications technology has been widely adopted in various application areas. Laptops and handheld devices such as PDAs have freed the computer from the confines of the desk or lab and have allowed the computer to go wherever workers may go or problems may be. Along with the recent advance in novel sensor technology, low-cost infrastructure monitoring has become a reality. We can expect that integrating such systems for the development of intelligent transportation system will help to improve driving safety effectively.

The vision of this project is to adapt the wireless sensor networking concept to the monitoring of transportation infrastructures. In this one-year pilot project, the research established a prototype test bed to evaluate these technologies in Iowa's environment and climate. The feasibility and issues of deploying a wireless sensor network for infrastructure monitoring were studied via the deployment and tests in the field.

1.2 Goals and objectives

The goals of this project were to evaluate the technical feasibility and cost efficiency of wireless sensor networks for transportation infrastructure monitoring. Based on the field test experience, the suitability and scalability of these technologies for practical deployment in other bridges were studied. The ultimate goal is that a public works employee assigned to the task of monitoring would only need to drive his truck to the proximity of the bridge that has a wireless sensor network deployed, then collect the data automatically to his laptop and perform the data analysis accordingly. It will improve the inspection efficiency and also the public workers working environment.

The specific objectives to achieve these goals were as follows:

1. Establish a listing of physical quantities that need to be monitored, and the requirements on monitoring.
2. Investigate sensor and data acquisition technologies salient to these quantities and select likely technologies for field implementation.
3. Establish the needed characteristics of mobile computers and wireless communication adapters.
4. Based on these characteristics test the available technologies and select a best fit.
5. Deploy a prototype test-bed unit in the field.
6. Acquire data and observations from this unit under a variety of conditions.
7. Investigate the feasibility of integrating existing infrastructure monitoring system using WAVE interfaces.

2. Literature review

2.1 Sensing technology for structure monitoring

Much recent work has appeared in the general area of novel sensor technologies. Daughton (2000) and Uchiyama and coworkers (2000) have applied novel magnetic materials in sensors for transportation applications. Swart and coworkers (1996) have successfully modified standard acoustic sensing techniques for road surface surveys. Rhazi (2006) has investigated the acoustic tomography technique, using measurement of P-wave travel time to assess the quality of concrete structures. Shen and coworkers (2000) have studied the important new technology of nano-fabricated mechanical components to develop mechanical sensors suitable for monitoring bridges. Zalt and co-workers (2007) has studied the usage of vibrating wire strain gauge and extrinsic Fabry Perot fiber optic sensors in bridge health monitoring. The Johns Hopkins University Applied Physics Laboratory (Carkhuff 2003) has developed a device, known as “smart aggregate” (SA) that is designed to be buried in concrete when a bridge deck is poured. It will be activated and send out data when it receives a RF signal from an external reading device.

Bak (1996) has investigated the important problem of "toughening" standard sensor technologies to the harsh environments present in transportation systems. A multiplexed optical fiber Bragg grating sensor system has been installed and tested over an 18-month period on a road bridge in Norway. A recent survey of the many current structural health monitoring and sensor technologies has been performed by Phares and Wipf and Greimann (2005). A fiber optic SHM system was developed and deployed on the US-30 South Skunk Bridge near Ames, IA and successfully demonstrated that continuous structural health monitoring system for bridges is feasible (Lee 2007 & Lu 2007). Most recently miniature Bragg Grating sensor Interrogators have been developed to be fitted in a 2cm x 5 cm package with low power operation by Mendoza and co-workers (2007).

2.2 Wireless sensor networks

Wireless sensor networks have drawn a great deal of attention recently because of its advantages and numerous potential applications. Their usage in structural health monitoring has been investigated by Paek (2005) and Chintalapudi (2006). The researchers Musiani, Lin and Rosing (2007) in UCSD presented a wireless sensing platform that combines localized processing with energy harvesting to provide long-lived bridge monitoring. The underground structure monitoring using wireless sensor networks have been studied by Li and Liu (2007). A bridge safety monitoring system has been developed using ubiquitous wireless sensor networks and the system has been installed on Gupo Bridge in Korea as a pilot project (RFID-USN, 2008).

One of the challenges that wireless sensor networks face is the energy efficiency and power supply problem. The wireless sensor nodes are in general battery-powered for easy installation and re-deployment by getting rid of cables. If the batteries have to be changed frequently, the deployment of a large scale wireless sensor network is impractical, if not impossible. The solutions to this problem are two-folds: 1) minimize the power consumption of the wireless sensor nodes, and 2) harvest energy from ambient environment. The first part can be achieved by adopting ultra-low power consumption IC chips and developing energy efficiency schemes and protocols for saving power. The second part is particularly attractive: if the nodes can achieve completely self-sustain ability by harvesting energy, it may eventually eliminate battery changes. Although renewable energy technology, such as solar panel and wind turbine, are relatively mature, they are in general for large-scale systems and not suitable for low-cost, small-sized wireless sensor nodes. Some pioneer projects have been undertaken to investigate the possibilities of harvesting energy from the ambient environment for low-cost, micro wireless sensors. Researchers at Clarkson University have developed a sensor node to harvest energy from passing traffic using an electromagnetic generator on a girder (Sazonov 2006). Another project is a wider European project called VIBES funded by the European Union to exploit vibration energy scavenging solutions (Torah, 2008).

2.3 Comparison of wireless Communication technology for WSNs

There are many options available for wireless communication technologies for wireless sensor networks (WSNs). IEEE 802.11 (or Wi-Fi) is the most popular air interface standard for Wireless Local Area Network (WLAN). Several revisions for the high data transmission rate of up to 300Mbps (802.11a/b/g/n) have been ratified. It is developed for customer-grade wireless data transmission and does not target to WSNs. The power consumption is excessive for many classes of sensor network applications. Alternative option is the wireless personal area network (WPAN) standards, including those of Bluetooth (IEEE 802.15.1), UWB (IEEE 802.15.3), and ZigBee (IEEE 802.15.4). Other wireless technologies, including wireless USB, IR wireless and Radio Frequency Identification (RFID), etc. Each of these standards is accompanied by advantages and limitations for sensor networks. Table 1 compares the specifications of wireless standards that have the potential to be adopted for WSNs.

For an infrastructure monitoring applications, it requires low power consumption for long term monitoring, and smaller size equipment/accessories for easy deployment. The data rate needed is typically not too high, and low cost is desired. Based on these characteristics of the infrastructure monitoring applications, IEEE 802.15.4 is the best candidate for our solution. IEEE 802.15.4 operates in the ISM radio bands, at 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz worldwide. IEEE 802.15.4 defines air interface, including the lower layers of the network communication protocol stack -- physical (PHY) and medium access control (MAC). ZigBee is the industrial consortium to promote and deal with interoperation of devices adopting IEEE 802.15.4 standard. Zigbee defines general-purpose, inexpensive self-organizing mesh networks that can be shared by industrial controls, embedded sensors, medical devices, building and home automation, and other applications. It provides network stack specifications: ZigBee/ZigBee PRO. The network is designed to use very small amounts of power, so that individual devices might run up to a year or two with a pair of AA batteries based on applications. A single ZigBee network theoretically can support up to a total of 65536 nodes, which is much more than other systems such as Bluetooth.

Table 1 Comparison of Specifications of Wireless Standards

	IEEE 802.15.4 (ZigBee)	IEEE 802.11a/ b/g/n (Wi-Fi)	Bluetooth	UWB	Wireless USB	IR Wireless
Operating Frequency	2.4 GHz 868 MHz (Europe) 915MHz (NA)	2.4 and 5 GHz	2.4 GHz	3.1-10.6 GHz	2.4 GHz	800-900 nm

Data Rate	20, 40, and 250 Kbps	up to 300 Mbps	1 Mbps	100-500 Mbps	62.5 Kbps	20-40 Kbps 115 Kbps 4 & 16 Mbps
Range	10-100 meters	50-100 meters	10 meters	<10 meters	10 meters	<10 meters (line of sight)
Networking Topology	Ad-hoc, peer to peer, star, or mesh	Point to hub Ad-Hoc	Ad-hoc, Point-to Point Point-to Multipoint	Point to point	Point to point	Point to point
Complexity	Low	High	High	Medium	Low	Low
Power Consump-tion	Very low	High	Medium	Low	Low	Low

IEEE 802.15.4 standard-compliant wireless transceivers are primarily from the following companies: CC2420/CC2430/CC2530 series from Texas Instruments ; MC1319x, MC1320x, MC1321x series from Freescale; and EM250/260 series from Ember. Low power consumption is crucial for deploying this type of infrastructure monitoring system in practice. According to the study on their power consumption specifications, we decided that the ChipCon series from Texas Instruments are with better power efficiency for the same transmit output power.

2.4 Wireless access for vehicular environment (WAVE)

Reliable, cost-efficient transmission of data back to local transportation control office is also another important issue that needs attention. The methods to transmit data back after they are collected by the individual sensor nodes vary. You may have public workers drive to the site to collect the data or transmit back via wide area networks, such as using data service of cellular networks. In this part we studied the possibility of adopting a WAVE system to transmit the data back.

The U.S. FCC has allocated 75 MHz of Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz to be used exclusively to vehicle-to-vehicle and infrastructure-to-vehicle communications in 2006. The DSRC is free but licensed spectrum and will solve the interference and co-existence problems of WLANs. The IEEE 802.11 WGp workgroup has been working on modifying the 802.11 wireless Local Area Networks (WLAN) standards to DSRC 5.9 GHz spectrum. The standard amendment 802.11p (2010) was just recently ratified in July 2010. IEEE trial-use standard 1609.1 to 1609.4 (2006) has defined the upper layer operations for WAVE system, including resource management, enhanced media access control (MAC) for multiple channel operation, networking and transportation layer, and security services. The IEEE 1609 standards support high-rate low latency communications (less than 200 microseconds) between WAVE devices, where IPv6 traffic and a specialized short message service. In the WAVE system, there are two main types of devices: Roadside Units (RSUs) and Onboard Units (OBUs). RSUs are typically considered to be embedded to the infrastructure and service provider, while OBUs operate when in motion and support information exchange with RSUs and other OBUs. Prototype IEEE 802.11p radios have been developed by the Vehicle Infrastructure Integration Consortium both for on-board and road-side units (Jiang, 2008). WAVE Prototype for Intelligent Transportation System (ITS) has also been developed by researchers (Xiang, 2008 and Ho, 2010).

Although a WAVE system is not originally designed to infrastructure monitoring, it may be used to implement the information dissemination. The road side units can be utilized to relay data back to a local transportation office where the data may be transmitted via Internet. Comparing to the data service of cellular networks, the advantages of a WAVE system is that the system is dedicated to transportation system. If the data collection of wireless sensor networks for infrastructure monitoring can be integrated into the safety part of the WAVE system, it will be more cost effective and will provide more reliable service. However, the WAVE system is still in its early development stage and implementing the infrastructure for WAVE system requires big investment. The system also needs to be tailored for infrastructure monitoring purpose. As wireless technology has helped solve difficult problems in many other contexts, it is clearly a promising technology worth investigating for transportation infrastructure monitoring.

3. System implementation and laboratory test

3.1 System Architecture

The proposed research will evaluate the use of a wireless sensor networks instead of PC-based systems for transportation infrastructure monitoring. The system implemented includes a base station and multiple end sensor nodes, as shown in Figure 1. The base station is connected to a laptop via USB port. An alternative option is use a base station with cellular network adapter to connect to Internet. The base station functions as a collector or coordinator to send commands to end sensor nodes and collect data from them. The end nodes perform the sensing and data collection job according to the configurable parameters such as sample rate, logging duration.

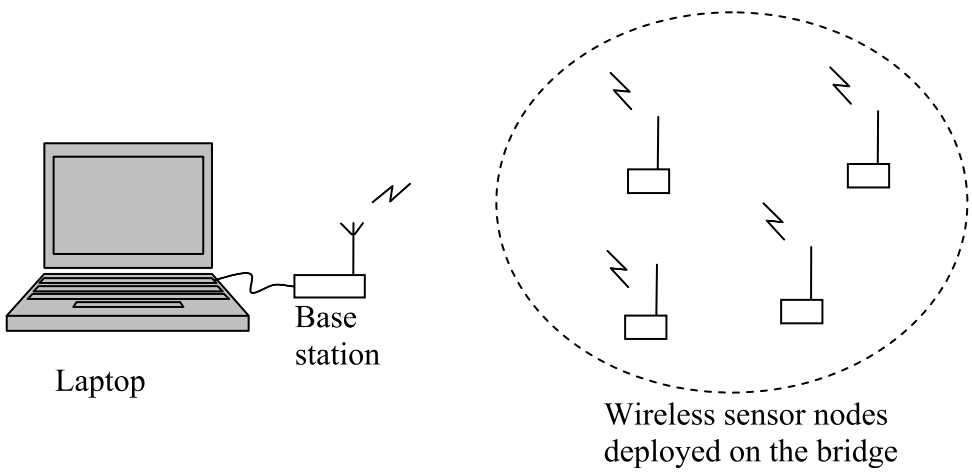


Figure 1 Diagram of the system prototype

3.1.1 Wireless sensor nodes and base station

We choose the SG-Link module from Microstrain as the platform for our development (Microstrain datasheet 2009). Mcirostrain is a company providing wireless sensor solutions to various monitoring applications. They provide software development kit for flexible implementation. The SG-Link module has programmable sensor interfaces compatible with a wide range of Wheatstone bridge type sensors. The base station and the SG-link node are shown in Figure 2.

Figure 2 Base station and wireless nodes used in the system

An end node consists of five basic modules: sensing and signal conditioning, communication, microprocessor, memory or storage, and power unit, as shown in Figure 3. A signal conditional circuit is used to convert the strain gage resistance change to a voltage signal and the output signal will be acquired in embedded end sensor nodes. The communication module has a radio transceiver and is responsible for communicating with base station or other nodes. The end nodes convert, process and transmit the signal remotely to the wireless collector node. The remote sensor nodes are battery powered. The SG-link sensor nodes use CC2420 chip for wireless transceivers for low power consumption and can easily work with Wheatstone bridge type sensors. They come with a 3.7V 200mAHour lithium rechargeable battery.

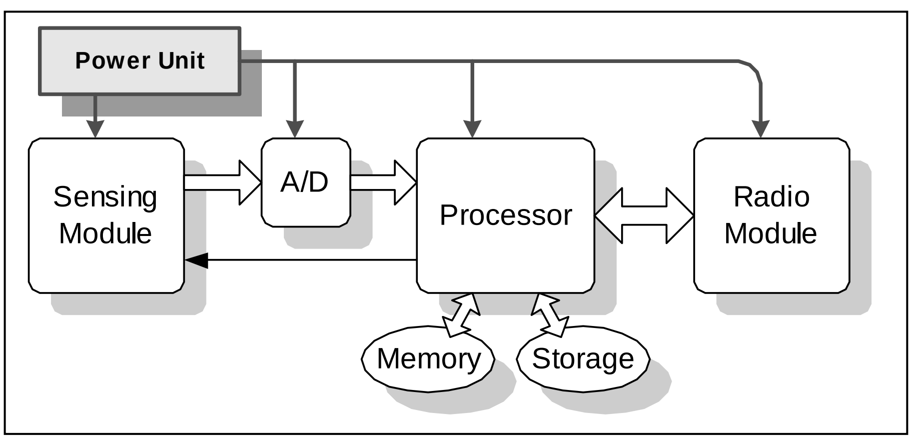


Figure 3 System block diagram for a wireless sensor

The physical quantities that need to be monitored in general include structure stress, crack, and others interested conditions such as temperature. The strain gages are commonly used to monitor the stresses of structural importance, so we work with strain gage first. In selecting the strain gage, we had to consider the availability, test duration, gage size, and self-temperature-compensation, ease of handling. For concrete structure, which is a mixture of aggregate and cement, it is desirable to use a strain gage of sufficient length to span several pieces of aggregate in order to measure the representative strain in the structure. It is usually the average strain that is sought in such instances, not the severe local fluctuations in strain occurring at the interfaces between the aggregated particles and the cement (Strain gage selection, 2007). For steel structure then the gage length is normally shorter.

Another consideration of the strain gage selection relates to the power consumption. Since the excitation voltage has to be higher enough to prevent high level of noises to be fed into the system, the smaller the resistance of the strain gage, the higher the power consumption will be. The commonly available strain gage size is 120 ohm, 350 ohm, and 1 Kohm. We choose 1 Kohm strain gage when other requirements are met. Otherwise 350 ohm strain gages were chosen. Figure 4 shows some strain gages we used for our experiments.

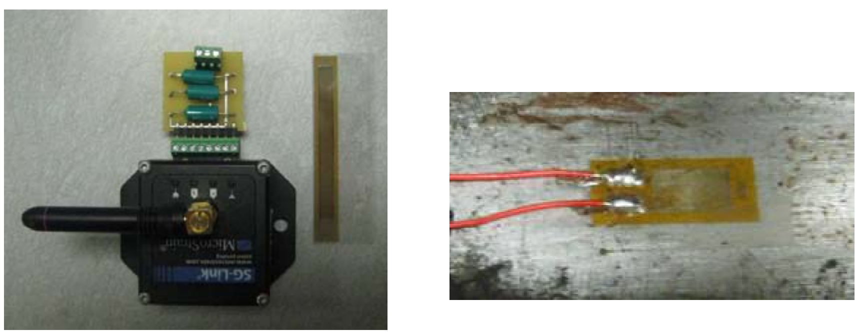


Figure 4 a) 2 inch strain gage for concrete with the wireless sensor node b) strain gage bonded to a steel specimen

3.1.2 LabVIEW program implementation

A LabVIEW program has been developed to interface the base station and configure the wireless sensor nodes for different sample rate and monitoring period, and downloading data and easy display for the downloaded data. The main interface of program is shown in Figure 5.

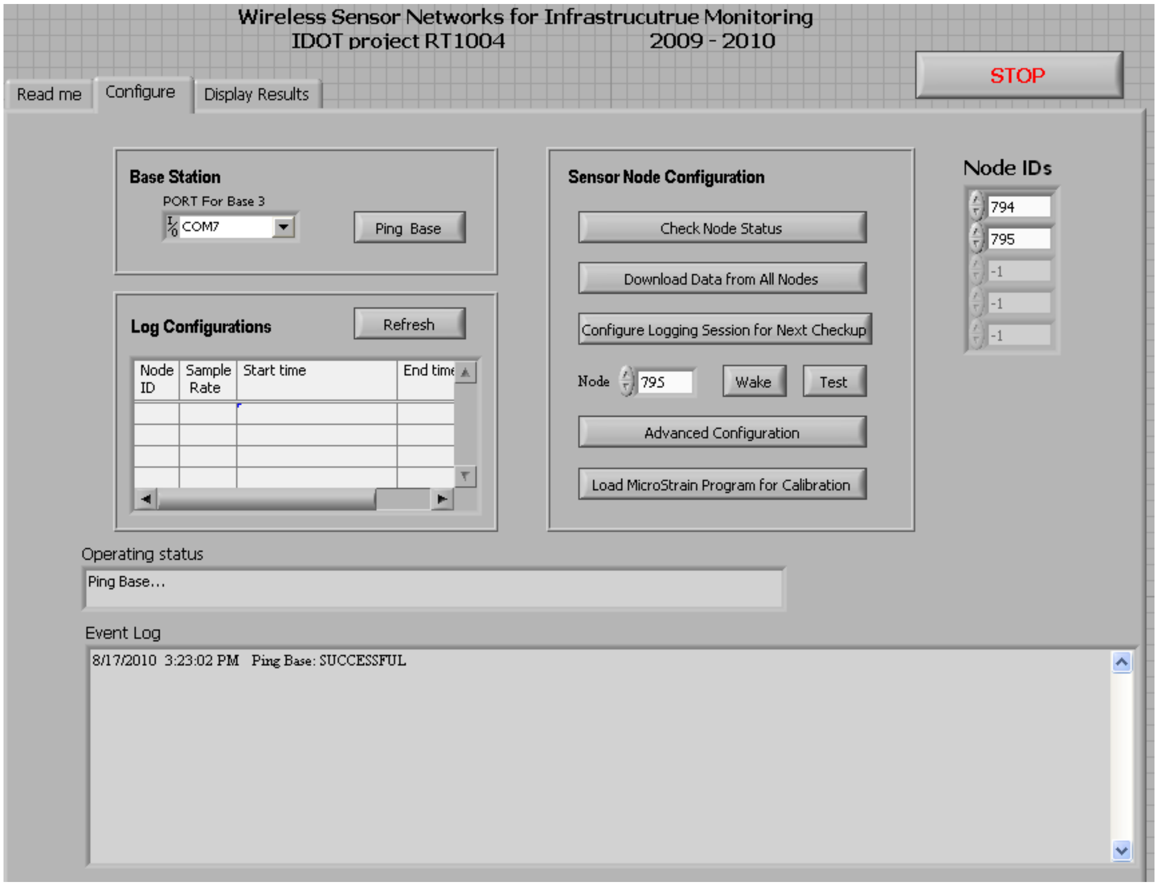


Figure 5 LabVIEW program user interface

The operations are easy to follow and explained briefly here: 1) Enter the IDs of the sensor nodes you use. Each wireless sensor node has a unique ID. The IDs need to be entered according to the nodes used in experiments. 2) Click on “Check Node Status” to check the status of all sensor nodes and make sure the communication between the base station and sensor nodes are good. 3) If there is any previous data log session set, Click on “Download data from all nodes”, otherwise skip this step. 4) Configure log session for next check up.

In the test mode, the sensor node may send data back to base station in real-time but it only allows one sensor to connect to the base station at the same time, as shown in Figure 6. In data logging mode, multiple sensor nodes can be enabled to collect data simultaneously within the same period for the given sampling rate, as shown in Figure 7. During the configuration, the system will prompt the user to download the data first

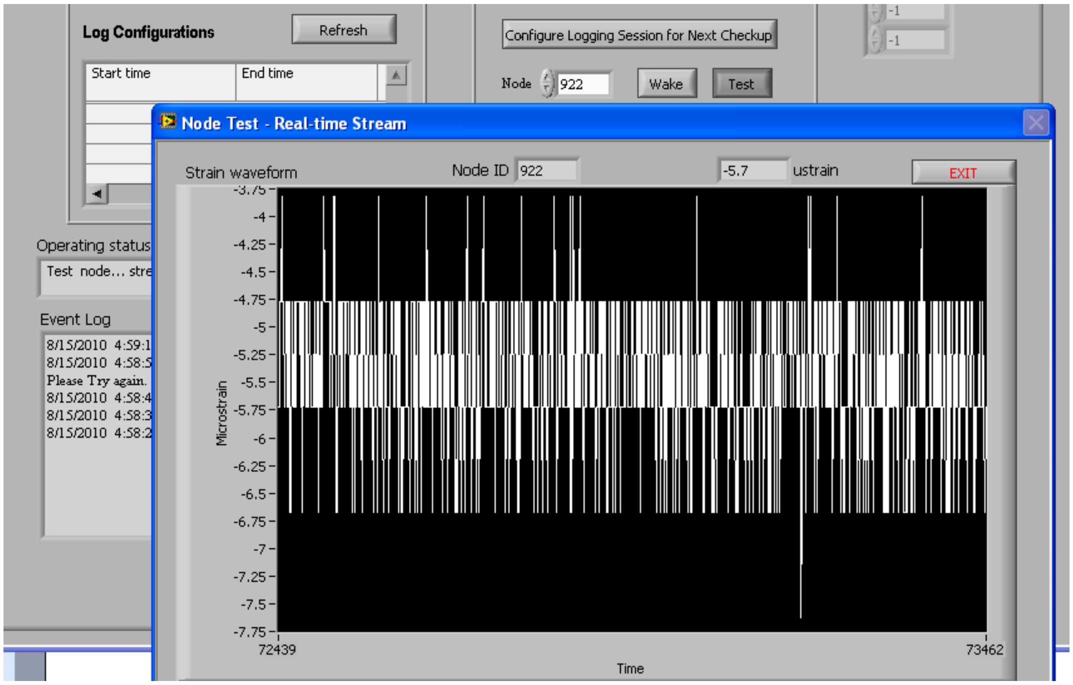


Figure 6 Real-time monitoring mode

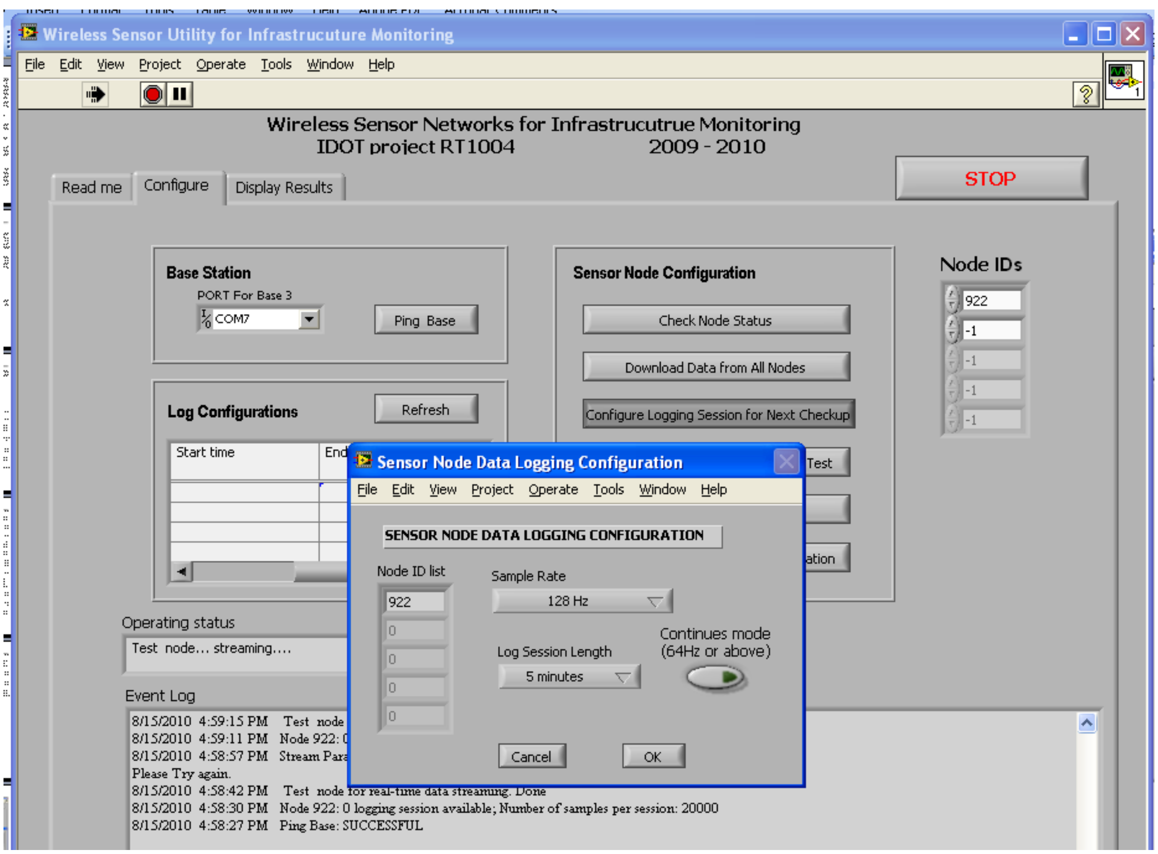


Figure 7 Data logging configuration window

before proceeding with new set of data collection. Once the data have been downloaded to the laptop, the on-board memory will be cleared. The available sampling rates are 64, 128, 256, 512 and 1024 Hz for normal operation and from 1 Hz to 1 sample per hour for low duty cycle logging mode. The sampling rate stability is ±25ppm for sampling rate 64Hz or above, ±10% for sample rate ≤ 1Hz. After the log session is configured, you may refresh the log configuration to get the most current configuration. The event log provides a convenient way to check what has happened.

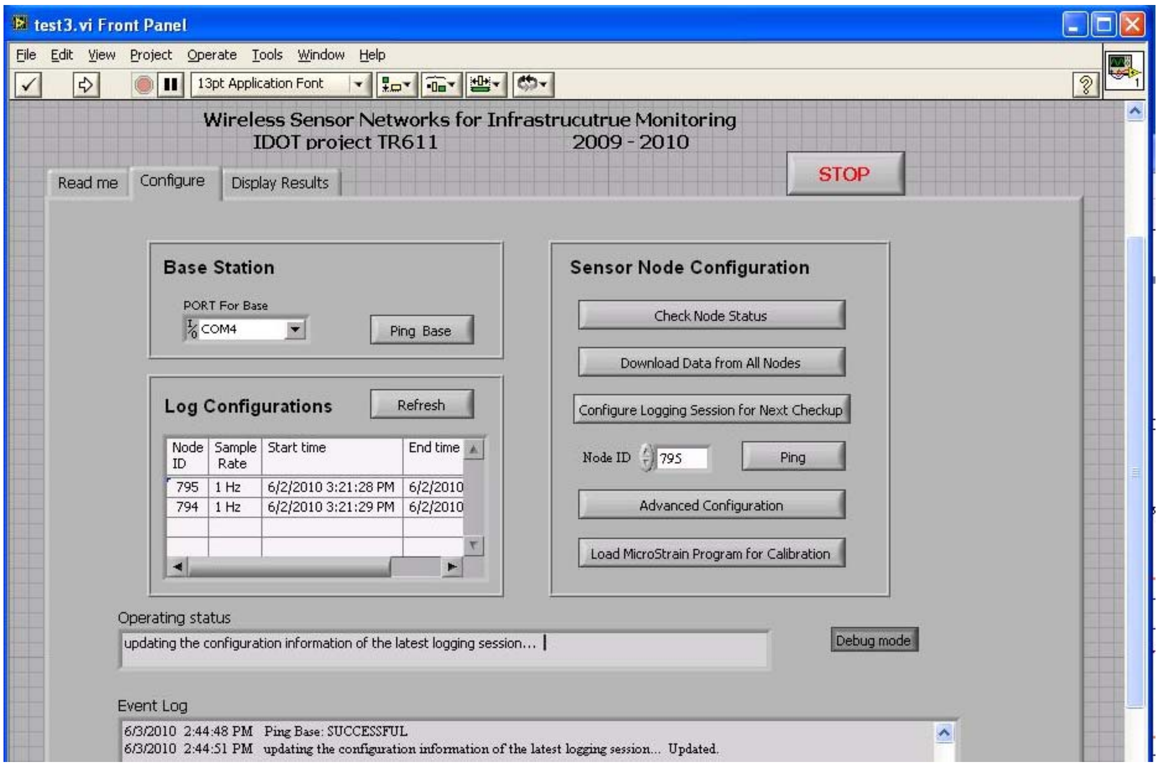


Figure 8 Refresh log configuration

When the sample rate is 1 Hz or lower, the nodes turn into sleep and only wake up for data collection according the sample rate to save energy. We call this working mode low duty cycle mode. The logging session limitation for low duty cycle is shown in Table 2. Each wireless sensor node has a 2Mbytes on-board memory. For normal data collection the user can choose how many samples (up to 65500 sample points) need to be collected for each logging session. For continuous data collection mode, the node will not stop collecting data until all 2 Mbytes of memory is full. The node will not respond to any command from the base station during its logging mode. For example, if the sampling rate is 128 Hz, the maximum logging session length is about 8 minutes for normal mode, after 8 minutes the node waits 300 seconds before it enters sleep mode to save energy. If continuous mode is enabled, it collects data for about five and half days unless it runs out of battery and during this period the node will not communicate to the base station. The length limitation on the data logging session for different sample rate is listed in Table 3. This is the drawback of the current version of SG-link nodes we used. If the sampling rate is 1Hz, then the logging session is up to 18 hours for normal log mode.

Table 2 Log session Limitation For Low Duty Cycle Mode

Sample rate	Maximal Logging period
1 Hz	18 hours
1 sample per 2 sec	36 hours
1 sample per 5 sec	3 days
1 sample per 10 sec	7 days
1 sample per 30 sec	22 days
1 sample per 1 min	45 days
1 sample per 2 min	90 days
1 sample per 5 min	227 days
1 sample per 10 min	454 days

Table 3 Log session limitation due to memory size

Sample rate	Maximal Logging period (non-continues mode)	Maximal logging period (continues mode)
1024 Hz	64 seconds	27 hours
512 Hz	128 seconds	54.5 hours
256 Hz	4 minutes	4.5 days
128 Hz	8.5 minutes	9 days
64 Hz	17 minutes	18.3 days

The downloaded data are stored in comma separated values files (.csv) and can be easily viewed either using the Display tab in the LabVIEW program or opened using Microsoft Excel.

3.2 Laboratory tests

3.2.1 Test on concrete specimen

The system was first tested on concrete specimen in Lab settings. The strain gage used is 20CBW-350. It is bonded to the midpoint of the concrete beam specimen of 6 inch square and 24 inches long after conditioning and preparing the concrete surface, as shown in Figure 9. The load is applied to the concrete specimen using a small Universal Testing Machine and the strain data are collected via the sensor nodes, as shown in Figure 10. One test data waveform is also shown in Figure 11. The loads were first increased approximately to 400lb then hold, and then to 800lb and hold, then release the load. The sampling rate is 1 Hz. The strain data is consistent with what the load applied to the specimen.

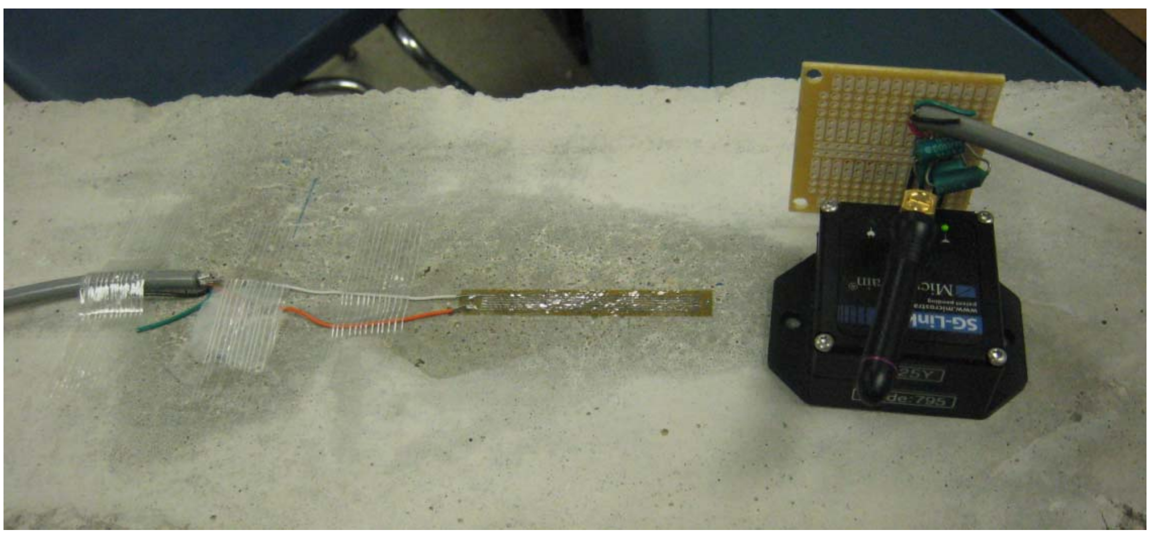


Figure 9 Installation of Strain gage on concrete specimen

Figure 10 Testing and collecting strain data on concrete specimen

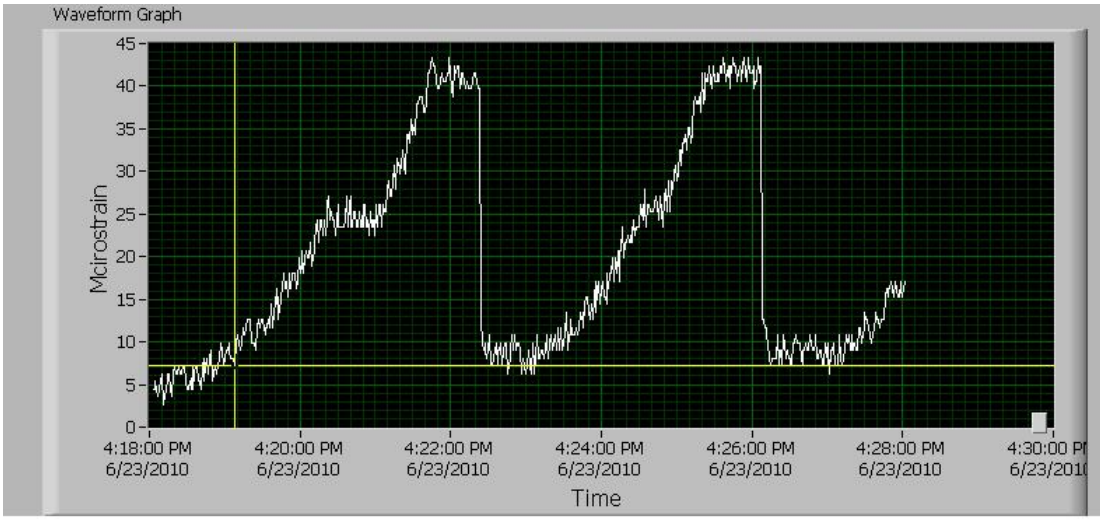


Figure 11 Test result on concrete specimen with load applied

3.2.2 Test on steel specimen

The system was also tested on steel A36 I-beam specimen 21 inches long. Two strain gages installed at the midpoint were utilized for the testing. The installed strain gages, one at the bottom surface of top flange, and the other at the bottom surface of bottom flange are shown in Figure 12. Two sensor nodes were used to collect the test data. During initial loading, and subsequent load release and reloading, the top flange at the midpoint experienced a little upward bending. Consequently, the strain gage at the bottom surface of the top flange has shown positive microstrain. The other sensor at the bottom surface of the bottom flange experienced usual positive microstrain. The test results with 1 Hz sample rate are shown in Figure 13.

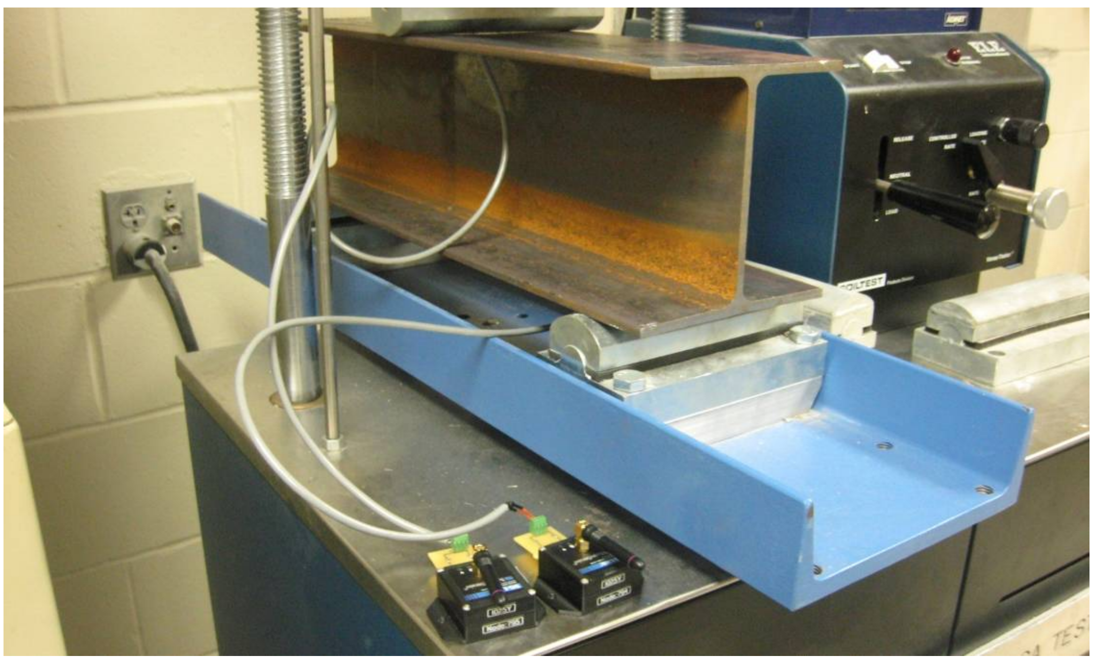


Figure 12 Testing and collecting strain data on steel I-beam specimen

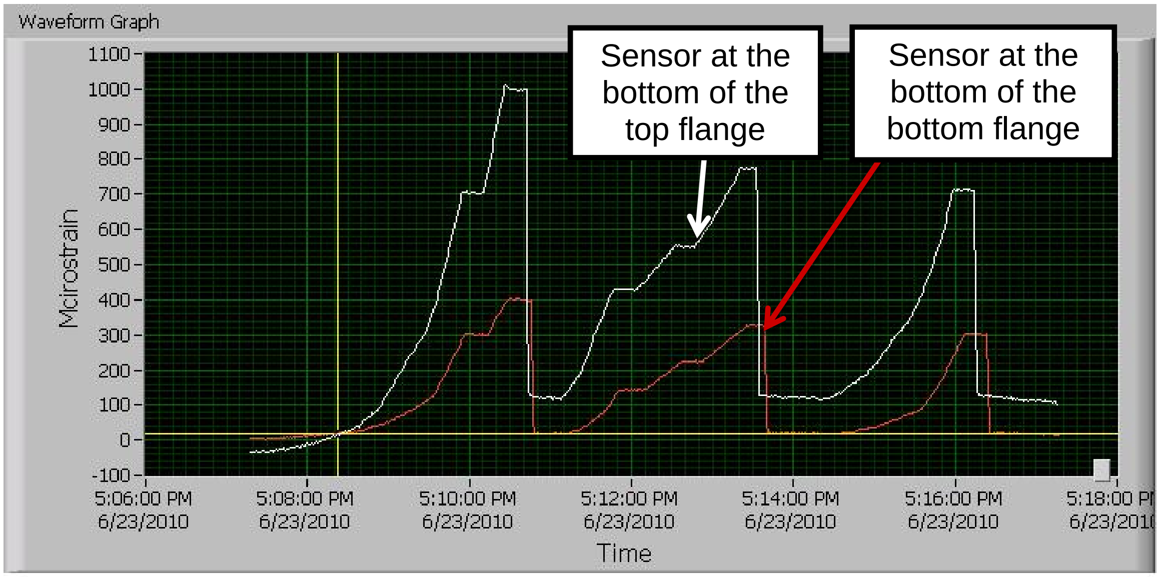


Figure 13 Test results on steel I-beam specimen

3.3 Energy efficiency analysis and lifetime estimation

In order to achieve cost-effectiveness and smaller sensor size, in general the individual sensor nodes present several limitations, such as limited energy and memory resources, small antenna, and limited processing capability. It is usually impractical to recharge nodes or replace the batteries frequently. Therefore energy efficiency is critical for practical deployment and each node must be as energy-efficient as possible. It is important to select low-power or power-management feasible devices. Besides, the implementation of effective power management algorithms and energy-efficient routing or communication protocols can further improve the energy-efficiency. In this part we will estimate the wireless sensor node lifetime under different scenarios.

The system used to measure the current consumption is shown in Figure 14. More information related to determination of current consumption is available in other studies (Martin 2003). The current consumption is obtained via measuring the voltage across a 10 ohm resistor that is in series with the power supply. The power supply current changes quickly as the node operates on different mode. So we used an oscilloscope to capture the voltage waveform to have a look of the current consumption as a function of time, which is necessary to determine the battery lifetime. A high precision 10 ohm resistor with 1%

tolerance is used in the experiments. This method may influence the results because of the insertion error of the external resistor and cable resistance, but it is considered negligible here.

In order to keep the power supply voltage in a consistent level, a TENMA power supply is used to provide a stable 3.3V instead of using batteries. Although it is different than batteries since battery voltage drops as used, this setup will provide more consistent results on current consumption. The impact of non-ideal batteries on its lifetime will be discussed later in this section.

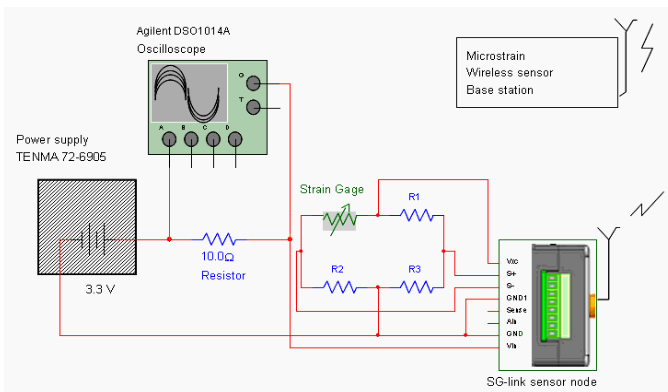


Figure 14 Power Consumption measurement setup

As we stated in previous session, the wireless transceiver CC2420 that use SG-link nodes is tailored for low power consumption applications. The current consumption for its receive mode and transmit mode are 18.8 and 17.4 mA respectively, while the current consumption is only 0.426 mA for IDLE mode (Voltage regulator and crystal oscillator on) and 0.02 mA for Power Down (only Voltage regulator on) mode (CC2420 datasheet). Thus one effective way to reduce the power consumption is turn the transceiver to Power Down mode until a transmission session is request or receiving is expected.

The SG-link node may stream data, i.e. sending sensing data directly to base station in real-time without saving it locally. It requires the base station to remain on all time. In this mode the power consumption is high and the batteries die quickly. If there is no activity for a given period (configurable), the node falls into sleep. In sleep mode, the node wakes up periodically to check if there is communication probe from base station. If not, it goes back to sleep. If it does detect the signal, the node will wake up and enter to idle mode. It is to be noticed that this idle mode is different from the IDLE mode defined in the CC2420. In this idle mode, the node turns on its receiver and listens on the media. Correspondingly, the power consumption is also relatively high even if the node does nothing. Another operation mode of the sensor node is logging mode. In this mode, the wireless sensors will collect data according to the configuration parameters (such as sample rate) and record the data to its 2MByte flash memory locally. The data may be downloaded later by the base station.

Varies scenarios were tested to obtain the power consumption results. Although we preferred to use 1 Kohm strain gage to minimize the power consumption, there were very limited options for strain gage at that size. we primarily used 350 ohm strain gages for our field tests. Power consumption during idle mode is shown in Figure 15. It can be seen the current consumption during idle mode is around 27mA (269mV/10Ω). Figure 16 shows the power consumption during logging mode with a sample rate of 10 Hz for 350 ohm sensor load. During low sample rate logging mode, the transceiver is turned off to save energy between two samplings. The pulses in Figure 16 represent the duration when the node samples and store the data. The current during sampling is about 14mA.

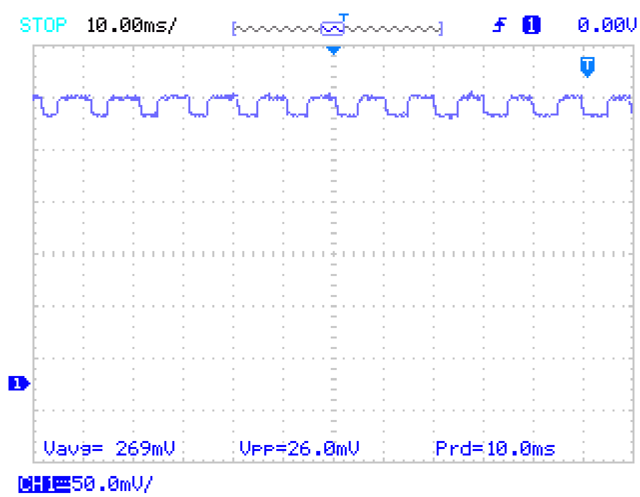


Figure 15 Power consumption during idle mode

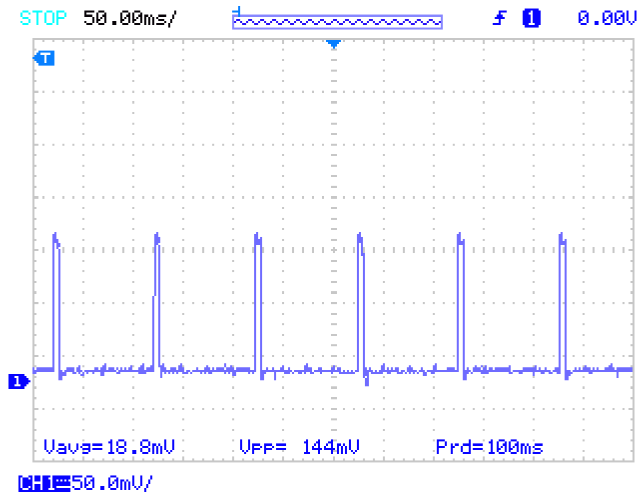
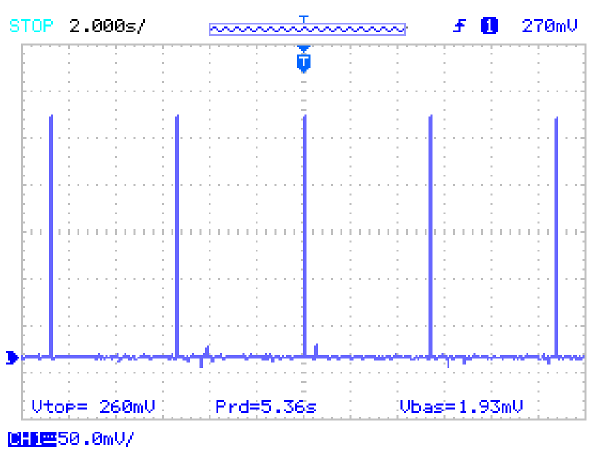
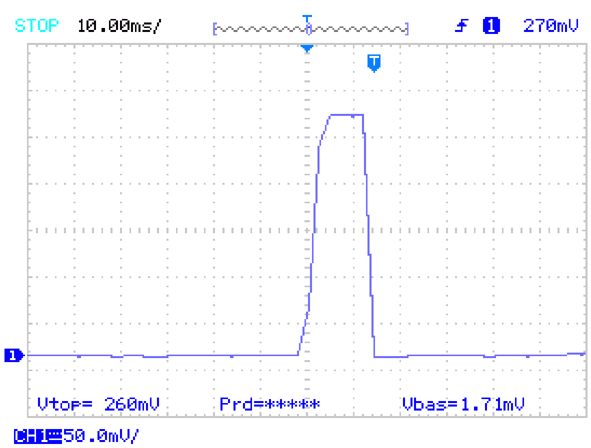


Figure 16 Power consumption during logging mode (10Hz sample rate)

The power consumption during sleeping mode is shown in Figure 17. The sleep interval is set to 5 second. It can be seen the power consumption during sleep is close to zero and it jumps to 26 mA (260mV/10ohm) when it wakes up to listen on media for a short period of 14 ms approximately in every 5.36 second period.

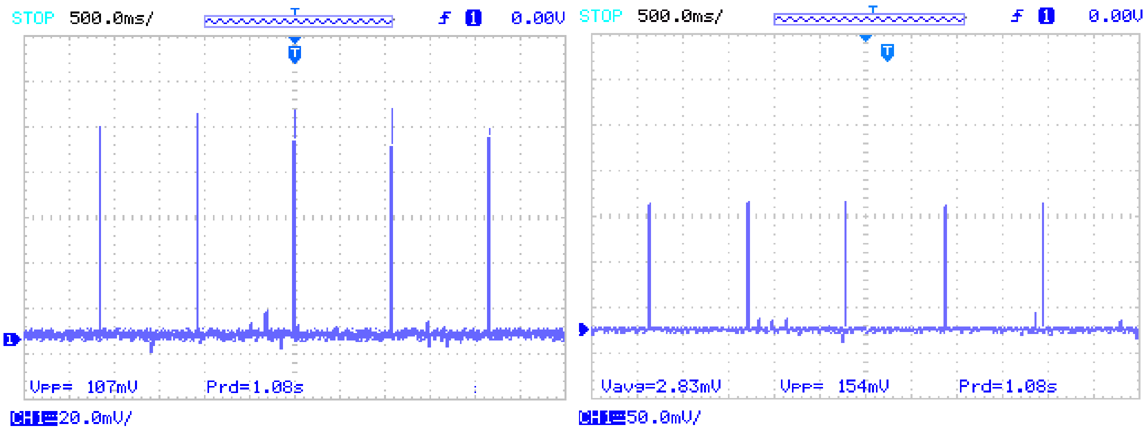




a) Wake up every 5 seconds from sleeping **b) a close-up look at the wake-up duration**

Figure 17 Power consumption during sleep mode

Our experimental results showed that in idle and sleep mode the power consumption does not relate to the sensor load, which is expected, since no excitation voltage is applied when there is no sensing task. While in stream and logging mode, the power consumption is different due to contribution of the different sizes of strain gage. Figure 18 compared the power consumption of low duty cycle logging (1Hz) mode for both 350 ohm and 1 Kohm sensor load.



(a) 1KΩ strain gage (b) 350Ω strain gage

Figure 18 Power consumption comparsion during low duty cycle logging mode

The average current consumption for different scenarios is given in Table 4. The average power consumption can be easily calculated by multiplying the current by the power supply voltage (3.3V here). It can be seen that the power consumption in sleep and low duty cycle (LDC) logging mode is low. Both power consumptions in sleep mode and in LDC mode with sample rate no more than 1 Hz are less than 0.9 mW, which is lower than 1% of the power consumption in real time steaming or idle mode. It also shows that when the sample rate is low, the difference between the average current consumption for 1Kohm and 350 ohm is negligible.

Table 4 Summary of Measured Power Consumption

Average Current consumption (mA)		Sleep mode (sleep interval 5 sec)	Idle mode	Real time streaming (Sample rate 736 Hz)	Low Duty Cycle Logging Mode Sample rate (Hz)			Normal Logging Mode Sample rate (Hz)	
					10	1	0.1	128	1024
Strain gage size	1KΩ	0.23	27	31	1.45	0.21	0.16	17	20
	350 Ω	0.23	27	34.1	2	0.24	0.17	20	23

To estimate the battery lifetime, we need to consider the following factors:

- Power consumption profile: The power consumption in different operation mode is fixed for a given node or hardware platform.

- Node operation configuration: The adjustable operation parameters of a node, such as sampling rate, sleep interval, the duration to wait before the node falls into sleep, have major impact on the lifetime. Since in idle mode it consumes significant power, a node may run out of the battery soon if it is does not enter sleep mode quickly after a data streaming or logging session.
- Battery capacity and properties: The battery capacity is typically given in terms of Ampere-hours or milliAmpere-hour that you can find on the batteries. The lifetime can be estimated by multiplying the capacity C by the battery's rated voltage, divided by average power consumption P. However battery's nonideal property may make the estimation overoptimistic (Martin 2003).

An ideal battery should have a constant voltage throughout the discharge that drops instantaneously to zero when it fully is discharged. In practice the battery voltage drops continuously over the discharge period until it drops below a given threshold. The discharge curve depends on the materials and the load. The capacity also varies with the value of the load and the temperature. The capacity may drop 40 percent for a pulsed load 200mA with a duty cycle 25% from the same constant load (i.e. 50mA) (Martin 2003). Since our application will have pulsed load both for sleeping and data logging mode, this property may affect the actual lifetime negatively. However, when the load is lighter, the capacity drop due to pulsed load is not that significant. For example, the capacity only drops roughly 8 percent for a pulsed load 68 mA with 25% duty cycle from the same constant load 17mA (Martin 2003). In our application, the peak load is no more than 35 mA, thus we expect the capacity drop due to pulsed high load is very small. In another hand, the recovery effect, which occurs when very light duty cycle is used to allow the battery to recover, will extend the battery lifetime.

We should also realize that the power dissipation of the voltage regulator on the board depends on the input/output voltage difference. It means that the higher the battery voltage is, the more power dissipation on the voltage regulator converting it to the desired output voltage. But since the voltage input range considered here is small, from 3.2V to 3.6V in our case, the results will be affected slightly.

It can be seen from above discussion that the estimated value could be overoptimistic if without careful consideration. In the following we will estimate the lifetime for two given scenarios. We assume a pair of Energizer Lithium AA batteries L91 is used. L91 battery for low drain applications will provide approximately full rated capacity over its lifetime (L91 datasheet). Since the required voltage input to the SG-link is 3.2V, we use the approximate capacity of L91 from 1.78 to 1.6V 1800 mA-hours as the battery capacity.

Scenario 1: Each logging session is 12 hours and sample rate is 1 Hz. After each logging session the node will on wake status for 5 minutes for data downloading and reconfiguration. 350 ohm strain gage is used. The estimated lifetime is:

$$T = 1800 \text{ mA}\cdot\text{hours} /[(0.24\text{mA}*12 \text{ hours} + 27\text{mA}*5 \text{ minutes}) /12.083\text{hours}]$$
$$\approx 4240 \text{ hours} = 176 \text{ days}$$

Scenario 2: Each session is 7 days and sample rate 10 Hz. After each logging session the node will on wake status for 15 minutes for data downloading and reconfiguration. 1Kohm strain gage is used. The estimated lifetime can be calculated as:

$$T = 1800 \text{ mA}\cdot\text{hours} /[(0.16\text{mA}*7*24 \text{ hours} + 27\text{mA}*15 \text{ minutes}) /168.25\text{hours}]$$
$$\approx 9005 \text{ hours} = 375 \text{ days}$$

Scenario 3: Each logging session is 8 minutes and sample rate is 128 Hz. After each logging session the node will on wake status for 5 minutes for data downloading and reconfiguration. 350 ohm strain gage is used. The estimated lifetime can be calculated as:

$$T = 1800 \text{ mA}\cdot\text{hours} /[(20\text{mA}*8\text{minutes} + 27\text{mA}*5 \text{ minutes}) /13\text{minutes}]$$
$$\approx 79 \text{ hours} \approx 3.3 \text{ days}$$

If the node is running in idle mode, the battery will die in around 2.7 days. From above analysis, it can be shown that a pair of the Lithium AA batteries could last from 6 months to more than 1 year for low duty cycle. The maintenance is minimal and it is feasible to deploy such system in the field for low duty cycle applications. However, if the sample rate is high the node has to be turned on all the time and the lifetime of the nodes is very limited, from several days to a couple of week depending on the parameters.

4. Field implementation and test

4.1 Communication distance

The transmission range we estimated is around 70 ft in the lab and more for open area. However for the field test, we found the distance is much shorter at the bridge we tested because of the communication environment. Both the abutments and I-beams in the bridge frame are steel which shields the RF signal completely and the concrete also absorbs RF signals significantly. We would like to have the laptop and base station located on the road side instead of under the bridge, so that the original antenna that is parallel to the bridge surface is not suitable anymore.

Based on the conditions stated above, we used antennas with vertical polarization. We need to decide the minimal antenna height. The sensor nodes are attached to the I-beam very close to the strain gage location. The distance between the antenna from bottom top of the bridge I-beam has to be at least more than 0.6 times of the first Fresnel zone so that the attenuation due to obstructions is not significant (Stallings, 2005) , as shown in the Figure 19.

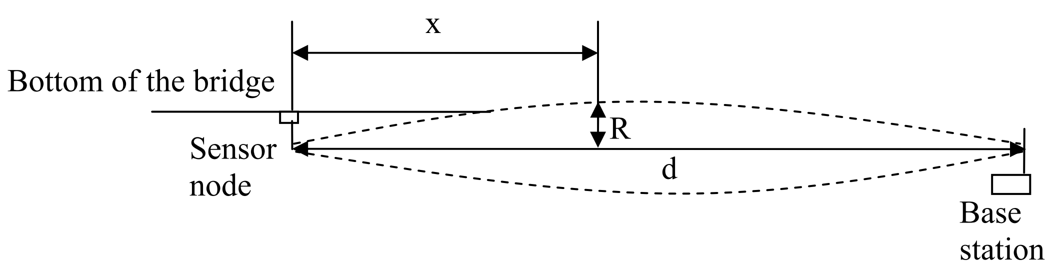


Figure 19 Fresnel zone and minimal antenna height

Consider the distance between a sensor node and the base station is *d* meters and the sensor node is *x* meters away from the bridge edge. Assume the RF wavelength is λ, then the first Fresnel zone radius R is given by

$$R = \sqrt{\frac{\lambda x(d - x)}{d}}$$

The minimal antenna height L should be 0.6R. Assume d=10 m and x = 4 m, then

$$L = 0.6 \times \sqrt{\frac{0.125 \cdot 4 \cdot (10-4)}{10}} = 0.33 \text{ meter}.$$

For d=15m, x= 6m, we have L = 0.4m. So the antenna has to be placed at least around 40 cm away from the bottom of the bridge surface.

Based on the free space path loss, the transmission distance can be estimated according to equation

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^\alpha}{G_r G_t \lambda^2}$$

where α is the path loss exponent (typically taking values between 2 and 4, depending on environment) and λ is the wavelength, and G_t and G_r denotes antenna gain of the transmitter and receiver, respectively. We can rewrite the equation in dB as follows

$$\Pr(dBm) = Pt(dBm) - \left[20\log(f) + \alpha \cdot 10\log(d) - G_r(\text{dB}) - G_t(\text{dB}) - 147.56 \text{ dB}\right]$$

Taking receiver sensitivity -85 dBm according to the IEEE 802.15.4 standard and the CC2420 transmit output power is 0 dBm, the RF frequency 2.4GHz, the transmission distance can be obtained as

$$d = 10^{(44.96 + Gr + Gt)/10\alpha}$$

Assume the path loss exponent α is 3.5, and normal bipolar antennas with 2.2 dBi are used, the estimated transmission range is around 25 meters. If high gain antennas with 7 dBi are used in both directions, the transmission range can be extended to 48 meters. However, we expect the actual transmission range should be much shorter than this estimation due to the bridge construction and without line of sight transmission. According to our test in the field, the transmission range is from 20-50 ft. The plants around the bridge, including trees and tall grasses, also affect the transmission range. Another method to extend the communication distance is to use 915 MHz transceivers, which is also one of the frequency IEEE 802.15.4 standard supports, instead of 2.4GHz.

It will roughly increase the transmission range by a factor of 1.6. However the data rate in this frequency is lower than that in 2.4 GHz, only around 40 Kbps.

4.2 Test on Blackhawk County secondary road bridge

The system was first tested on the Ashley-Brian bridge, north of the La porte city. After the system functions were verified in outdoor environment, the load test was performed on a new bridge on Ansborough Avenue, Blackhawk County (W. Sec9, T-87N, R-13W). The construction of the bridge was completed in July 2010 and pictures are shown in Figure 20. This is a 34’ x 30’ bridge with 8 composite beams in slab, as shown in Figure 21.

(a) Top view **(b) Bottom view**

Figure 20 Ansborough Bridge, Blackhawk County

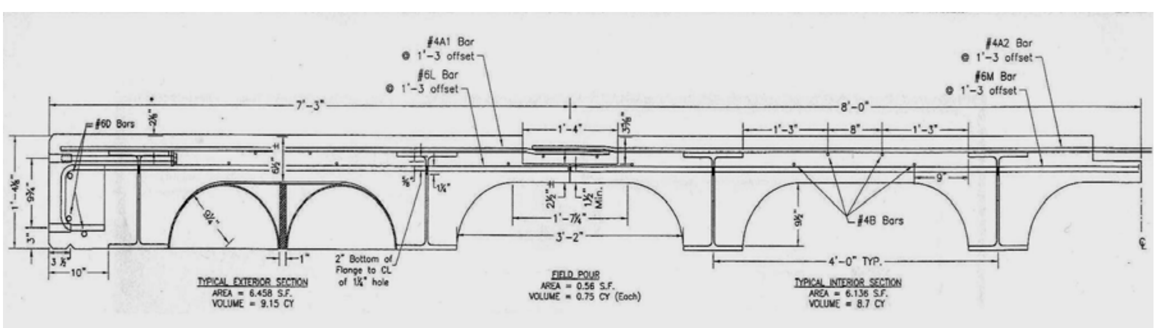


Figure 21 Bridge framing plan (Courtesy: Black Hawk County, IA)

Tests were performed to verify the functionality of the system uncontrollable outdoor environment, such as very high humidity (95% or higher) before the load test. In Figure 22, three different strain gages (2 inch length strain gage with node 795, 0.25″ one with node 926 and 0.5″ one with node 794) are applied to the mid-point of the I-beam 2 and some test results are shown in Figure 23 and Figure 24.

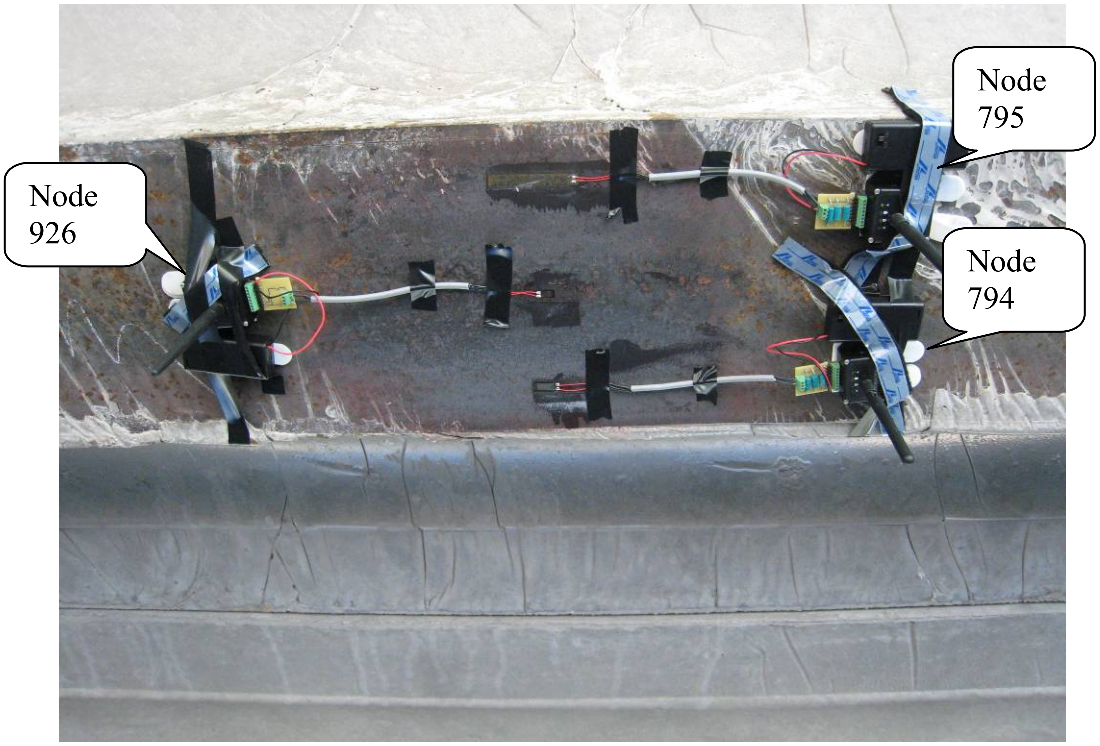


Figure 22 Three strain gages applied to mid-point of I-beam 2

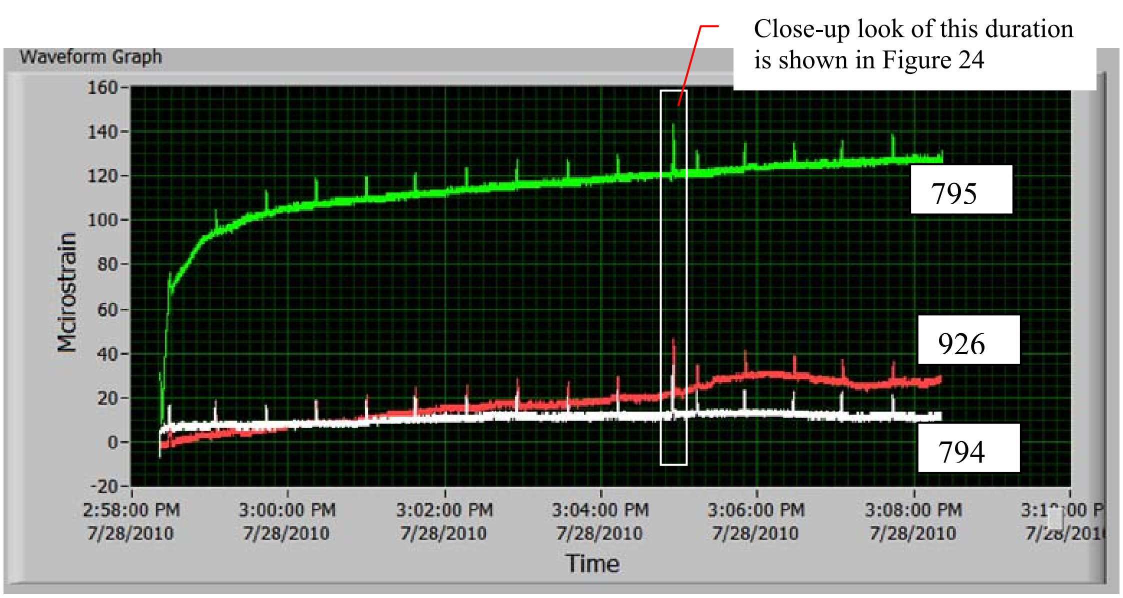


Figure 23 Results of three different strain gages

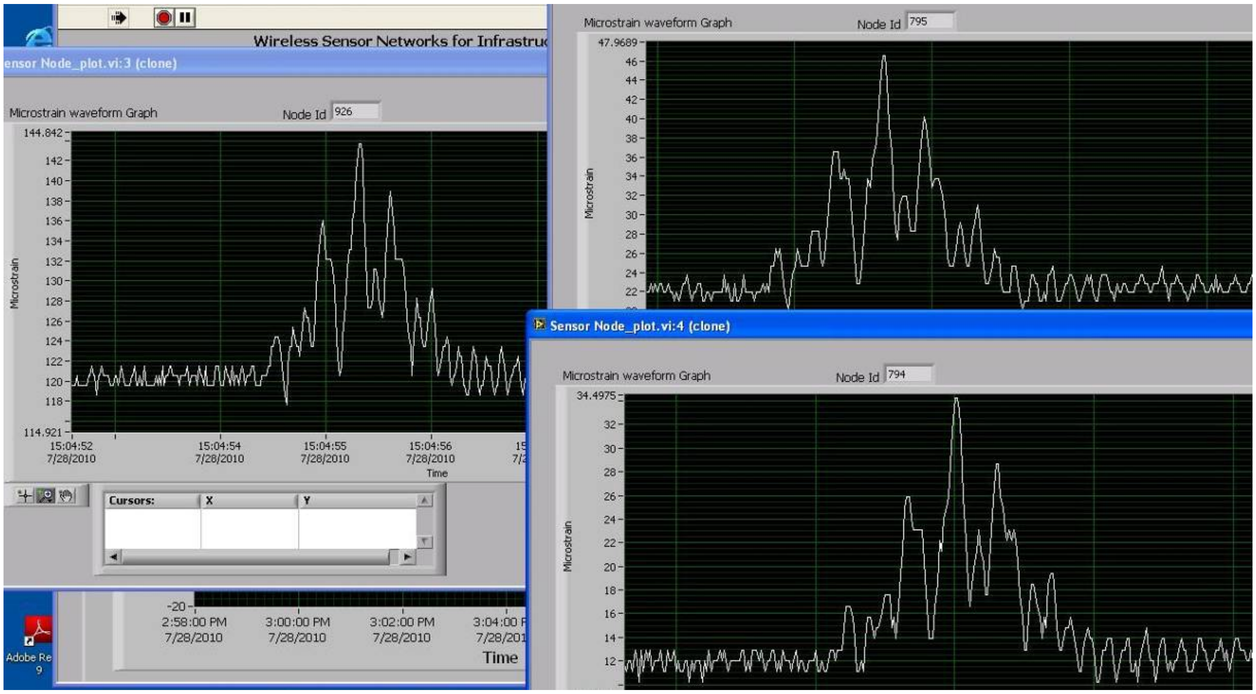


Figure 24 Close-up look of the results

By comparing the results from three different strain gages, it can be seen that all three strain gages can catch the dynamic strain well and the results are consistent. However, the drift for 2 inch strain gage is very large within the ten minutes monitoring period. The 0.25″ strain gage is more sensitive and susceptible to the noise. The 0.5″ strain gage is more stable and still able to catch the needed dynamic strain.

In Figure 25, some test results of four 0.5 inch strain gages that were applied to the mid-point and quarter-point of the I-beam 2 and 4 respectively are displayed. The sample rate is 128 Hz. The test was done by driving a mini-van over the bridge back and forth. A peak of the strain can be observed when the van crossed the bridge. It can be seen, the results are consistent but with some offset. This problem can be easily solved by shifting the waveform with the offset constant.

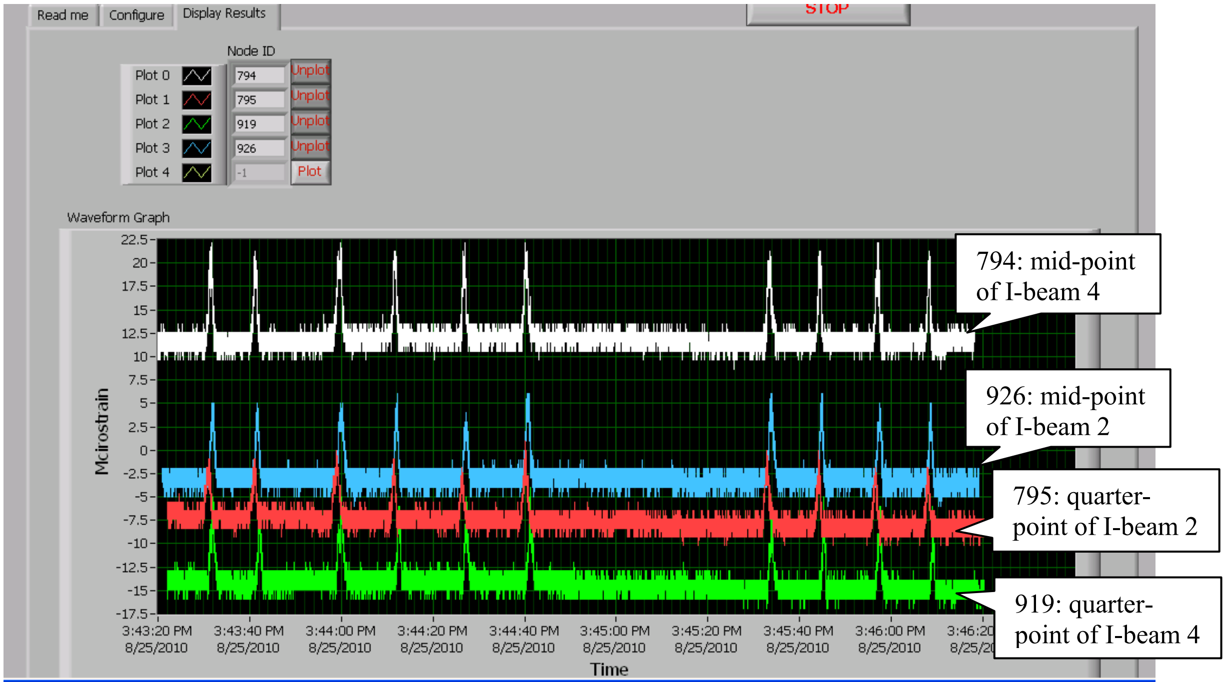


Figure 25 Strain gage test results sample

4.3 Load test results

Load test on Ansborough Bridge was performed on August 30, 2010. In the first test, two sensor nodes were placed on the mid-point of the top of the bottom flange of I-beam 2 and 4, respectively, as shown in Figure 26. Figure 27 shows the picture of one of the mounted sensors under the bridge.

Two standard tandem-axle dump trucks loaded to a gross weight of approximately 56 kips each were utilized for load testing, as shown in Figure 28. One truck crossed the bridge at a speed of approximately 2 miles/hour while the other truck was parked on the bridge deck at designated locations. The positions of the loaded trucks were determined based on the truck axles, loads, and bridge beam locations. Several loading sequences were applied to the bridge in order to capture maximum microstrain. To record all details of possible strains, the sample rate used for load tests is 128 Hz. It can be seen from the test results shown in Figure 30 that the maximum tensile strain on the I-beam 4 and I-beam 2 are 154 and 149 microstrain respectively.

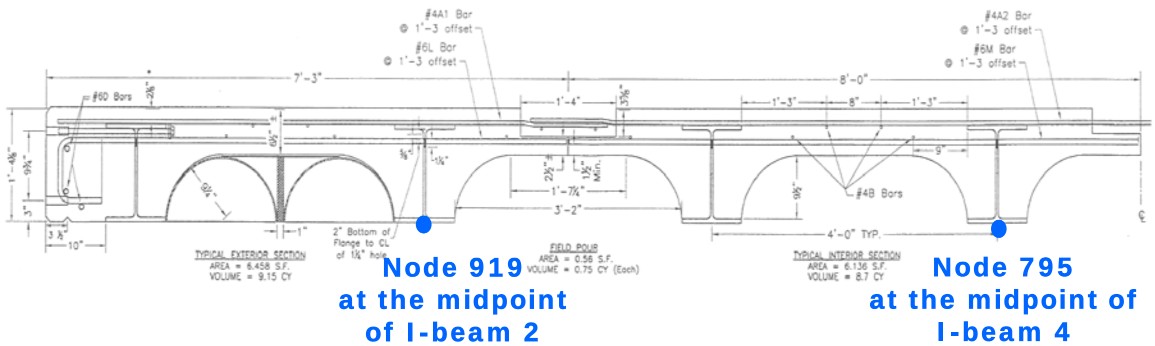


Figure 26 Sensor locations on the Ansborough bridge for load test 1

Figure 27 Mounted wireless sensor node under the bridge

Figure 28 Two loaded dump trucks for load test

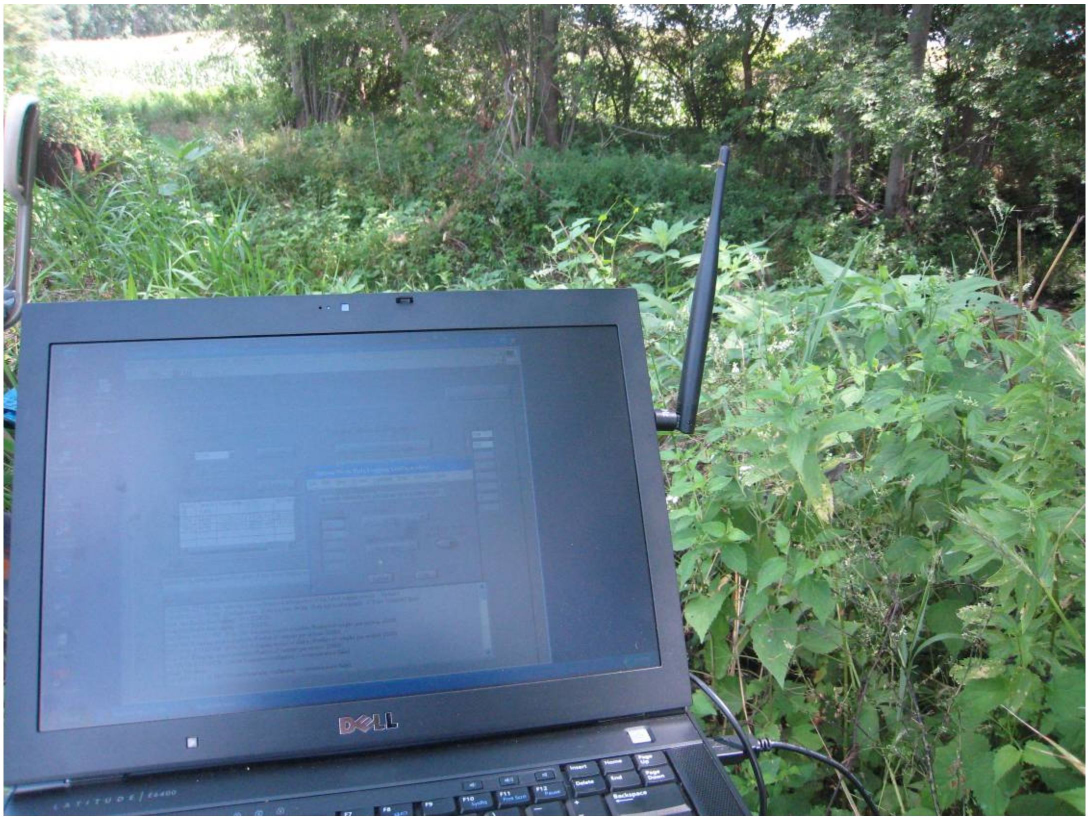


Figure 29 Configuring wireless sensor nodes using laptop

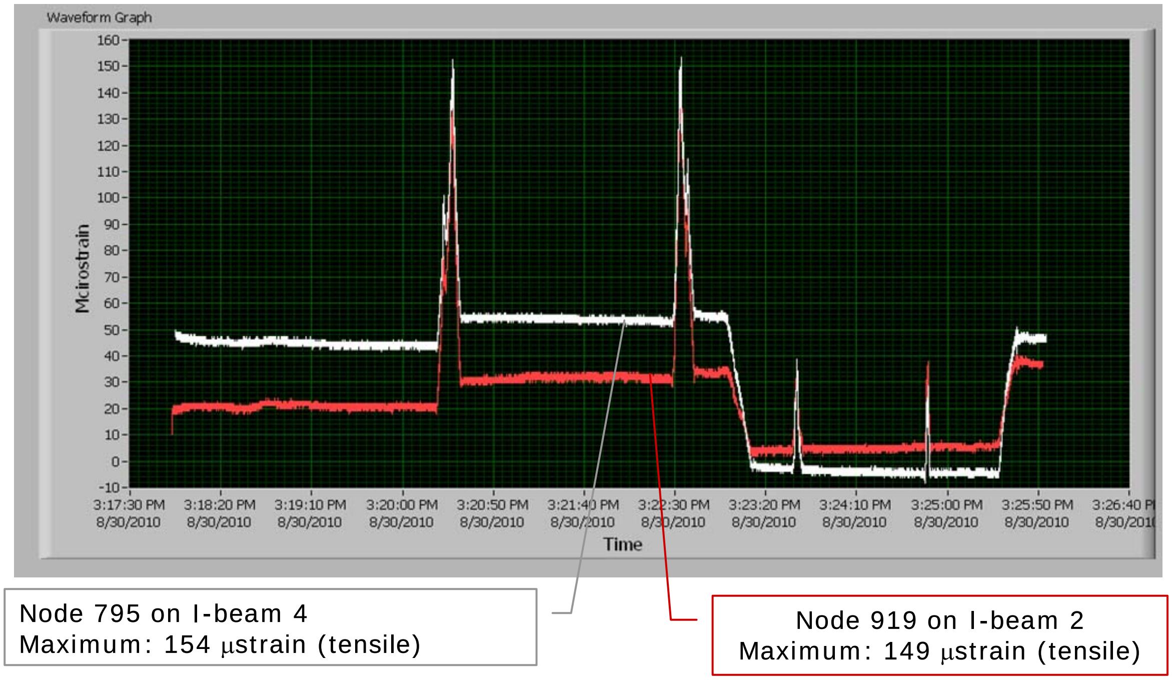


Figure 30 Load test results on I-beams

The second load test was performed to obtain both the peak compression and tension strains. Sensor node 919 was placed approximately at the center of the top surface of bridge deck, and sensor node 795 was placed on the top of the bottom flange of I-beam 4 under the bridge, as shown in Figure 32. The test results are shown in Figure 33. The maximum tensile strain detected in node 795 is 154 microstrain which is same as the first test. The maximum compression strain, detected in node 919 on the concrete surface is -88 microstrain. For the purpose of analysis, maximum steel and concrete strains are rounded off to 155 and 90 microstrain respectively. Concrete of 6 ksi (f_c') and steel of 50 ksi (F_y) were used for the composite bridge structure. The calculations presented in Table 5 reveal the maximum tensile stress in steel and maximum compressive stress in concrete due to applied loading conditions. As can be seen in Table 5, maximum tensile stress in steel is 4495 psi, and the maximum compressive stress in concrete is 397.37 psi. Black Hawk County engineers have reviewed these results, and based on the design data, these values are well within acceptable limits for this bridge.

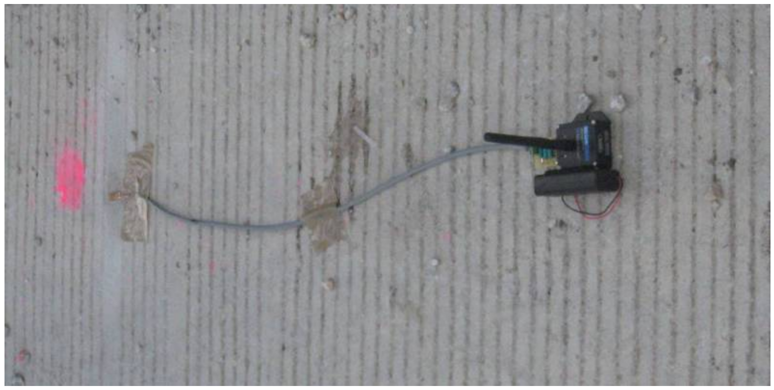


Figure 31 Sensor node applied on the bridge top surface

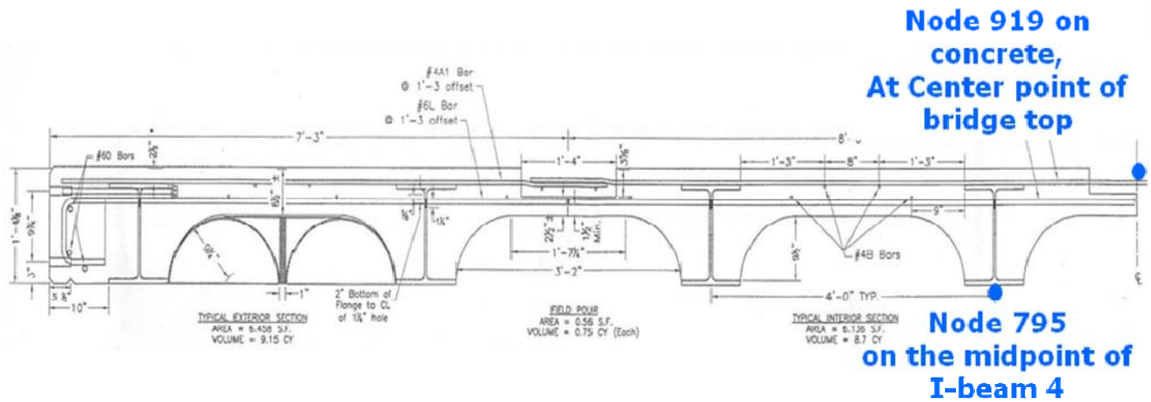


Figure 32 Location of sensors for load test 2

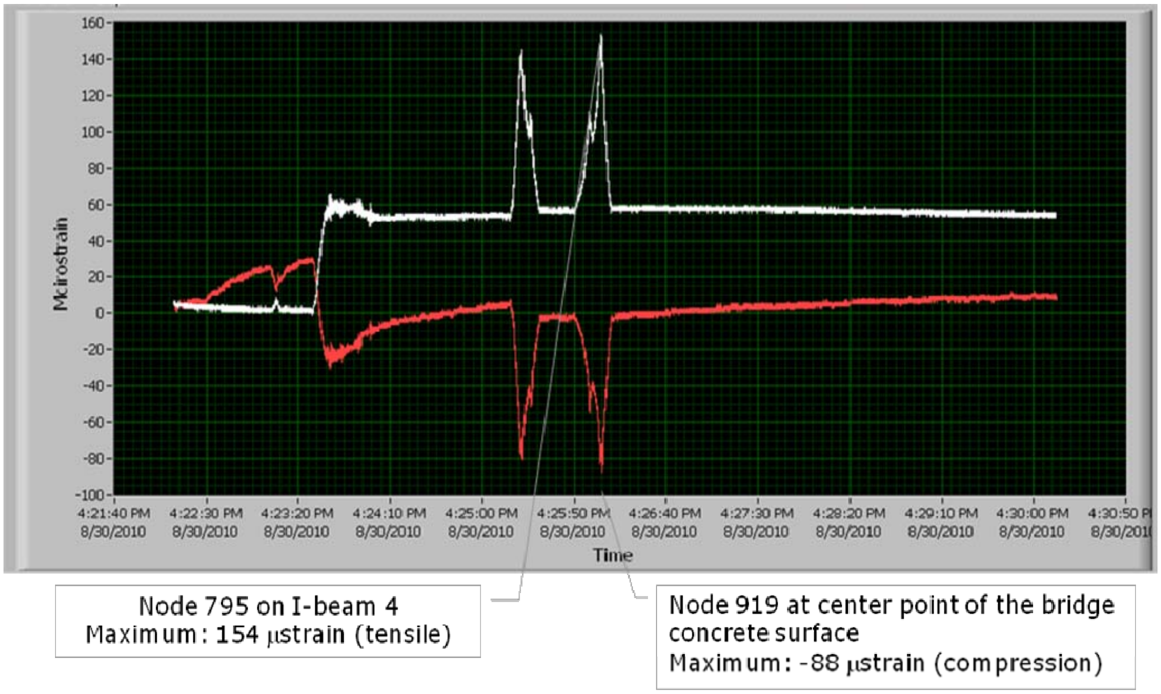


Figure 33 Strain results for load test 2

Table 5 Tensile and Compression Stress Summary and Calculation Parameters

Fy =	50,000	psi	
f'c =	6000	psi	
E steel =	29,000,000		
E conc =	4415201		
L =	34	ft	
Concrete	1006.71	lb/ft	
Steel	61.000		
	1067.71	1.067714	k/ft
M =	154.285	k-ft	
fs =	20.080	ksi	

	Max Strain	E	Stress	Units
LL tensile stress =	155	29	**4495.0**	**psi**
LL comp stress =	90	4.4152	**397.37**	**psi**

4.4 Discussions

Attaching the sensor nodes is easy and quick. Since the nodes are light weighted (50g plus antenna and a pair of AA batteries), we used some picture hanging removable interlocking fasteners to stick on the bridge surface and the nodes can easily be attached and removed for reuse in other places. The primary issue of the system installation is to apply the resistance type strain gage to the bridge surface. The surface preparation has to follow the instructions carefully to obtain reliable strain results. The bonding to steel I-beams is quick but the bonding to the concrete often takes longer and cause trouble. Though the cost of resistant type strain gages is low (around ten dollars each), they may not be reused.

The battery lifetime is another issue to be discussed. For low duty cycle application (sample rate lower than 1Hz), the lifetime of a pair of AA battery is reasonable, from 6 months to a year. However, in order to catch the dynamic strain details, the sample rate has to be much higher. For example, assuming vehicles driving in 60 miles/hour, the sample rate at least needs to be 125 Hz, according to recommendations from technical advisory committee for this project. Working on sample rate 125 Hz or higher, the wireless sensor nodes cannot go to sleep mode and drain significant power, so that a pair of AA batteries can only last for several days. Several methods may be used to address this issue, including adopting other types of strain gages for different focus, and energy harvesting from ambient environment.

5. Conclusions and recommendations

The application of wireless sensor networks in infrastructure monitoring is promising. In this study, a monitoring system using wireless sensor nodes was installed on a 34 feet span composite beam and slab bridge in Balck Hawk County, Iowa. The bridge is located on Ansborough Avenue, a secondary road in the County. Two standard tandem-axle dump trucks loaded to a gross weight of approximately 56 kips each were utilized for load testing. Several loading sequences were applied to the bridge with the loading trucks to obtain maximum effects at various locations in the superstructure. The installation of the system was quick and convenient. Reliable performance of the wireless monitoring system was encountered. A robust communication between the wireless sensors and the data repository ensured 100% success rate in data delivery. As the truck crossed the bridge, data were continuously recorded at multiple sensor nodes. The downloaded data can be displayed on a graphical output screen on a laptop (microstrain in this case). Each wireless sensor node approximately costs $500 and it is expected the cost will further go down over time. However, several issues need to be addressed in order to make wireless sensor networks more feasible and accessible in bridge health monitoring. The followings are the recommendations for further investigation.

1. For long term monitoring, battery powered wireless sensor nodes can have reasonable lifetime if the sample rate for the monitored variables is 1 Hz or lower. For applications such as dynamic strain monitoring that requires high sample rate (frequency) the lifetime of sensor nodes is limited. Because of the limited lifetime and performance of the resistance type strain gages, feasibility of other types of alternative sensors such as vibrating wire gages needs to be explored.

2. Though the technology is not in its early stage, energy harvesting from ambient environment is very attractive for the long term remote monitoring. In order to

implement a self-sustainable system, the demanded energy for an application needs to be carefully studied to make sure that the system can still provide reliable service when only low ambient energy is available. Efficient energy conversion and conservation methods dealing with ultra low voltage and low energy source are the key.

3. Additional solutions based on vibration, strain, and thermal energy from the local environment can be explored to extend the functionality of the wireless network system without the need for battery replacement.

Reference:

Bak, David J., Contacting sensor withstands shock and vibration, Design News, July 22, 1996, v51, n14, p65(1) .

Carkhuff, B.; Cain, R.; Corrosion sensors for concrete bridges, IEEE Instrumentation & Measurement Magazine, v.6, no.2, June 2003, p19(6).

Chintalapudi, Krishna, et al., "Monitoring Civil Structures with a Wireless Sensor Network," IEEE Internet Computing, vol. 10, no. 2, pp. 26-34, Mar/Apr, 2006.

Daughton, James M, GMR and SDT Sensor Applications, IEEE Transactions on Magnetics, Sept 2000, v36, i5, p2773.

FHWA Bridge Programs NBI Data: Bridges by state and county (As of August 2009). http://www.fhwa.dot.gov/bridge/nbi/county09.cfm#ia

Ho, Kai-Yun, Kang, Po-Chun, Hsu, Chung-Hsien, and Lin, Ching-Hai, Implementation of WAVE/DSRC Devices for Vehicular Communications, Proceedings of 2010 International Symposium on Computer, Communication, Control and Automation.

IEEE Standard 802.11 – 2007: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 2007.

IEEE Standard for Information technology -- Telecommunications and information exchange between systems -- Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput, 2009.

IEEE Standard 802 Part 15.1: Wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs), 2005.

IEEE Standard 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)

www.zigbee.com

IEEE Standard 802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: amendment 6: Wireless Access in Vehicular Environment, 2010.

IEEE Trial-Use Standard 1069.1: Wireless Access in Vehicular Environment (WAVE) – Resource Manager, 2006.

Jiang, D. and Delgrossi, L. , IEEE 802.11p: Towards an international standard for wireless access in vehicular environments, Proceedings of IEEE 2008 Vehicular Technology Conference, 11-14 May 2008, p.2036-2040

Lee, Y., Phares, B., and Wipf, T., Development of a low-cost, continuous structural health monitoring system for bridges and components, Proceedings of the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2007.

Li, Mo and Liu, Yunhao, Underground structure monitoring with wireless sensor networks, Proceedings of ACM 6th International Symposium on Information Processing in Sensor Networks, 25-27 April 2007, p69(10).

Lithium L91L92 Application Manual. Available at http://data.energizer.com/PDFs/lithiuml91l92_appman.pdf

Lu, P., Wipf, T., Phares, B., and Doornink, J., A bridge structural health monitoring and data mining system, Proceedings of the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2007.

Martin, Thomas L. and Siewiorek, Daniel P., Nonideal battery prosperities and their impact on software design for wearable computers, IEEE Transaction on Computers, August 2003, Vol. 52, No. 8, pp. 979-984.

Mendoza, E., Kempen, C., Panahi, A., and Lopatin, C., Miniature fiber Bragg grating sensor tnterrogator system for use in aerospace and automotive health monitoring systems, Proc. of SPIE Photonics in the Transporation industry: Auto to Aerospace, Vol 6758, p0B-1(10), October 2007.

Musiani, D.; Lin, K.; Rosing, T.S.; Active sensing platform for wireless structural health monitoring, Proceedings of ACM 6th International Symposium on Information Processing in Sensor Networks, 25-27 April 2007, p390(10).

Paek, Jeongyeup; Chintalapudi, K.; Govindan, R.; Caffrey, J.; Masri, S.; A Wireless Sensor Network for Structural Health Monitoring: Performance and Experience, Proceedings of 2nd IEEE Workshop on Embedded Networked Sensors, 30-31 May 2005, p1(10).

Phares, Brent; Wipf, Terry; Greimann, Lowell, and Lee, Yoon-Si, Health monitoring of bridge structures and components using smart structure technology, Technical reports for Wisconsin Highway Research Program, January 2005.

RFID-USN leading to the ubiquitous world and 2006 pilot projects, Korea National Information Society, February 2008.

Rhazi, J., Evaluation of Concrete structures by the acoustic tomography technique, Structrual Health Monitoring, 2006, v5(4), p333(10).

Sazonov, Edward, et. al., Wireless Intelligent Sensor and Actuator Network (WISAN): a scalable ultra-low-power platform for structural health monitoring, Proceedings of SPIE's Annual International Symposium on Smart Structures and Materials, San Diego, CA, 2006.

Shen, L. P.; Mohri, K.; Uchiyama, T.; Honkura, Y., Sensitive acceleration sensor using amorphous wire SI element combined with CMOS IC multivibrator for environmental sensing, IEEE Transactions on Magnetics, Sept 2000, v36, i5, p3667.

Stallings, William, Wireless Communications and Networks, Pearson Prentice Hall, 2005.

Swart, Pieter L.; Lacquet, Beatrys M.; Blom, Christiaan, An acoustic sensor system for determination of macroscopic surface roughness, IEEE Transactions on Instrumentation & Measurement, Oct 1996, v45, n5, p879(6).

Uchiyama, T.; Mohri, K.; Itho, H.; Nakashima, K.; Ohuchi, J.; Sudo, Y., Car Traffic Monitoring System Using MI Sensor Built-In Disk Set on the Road, IEEE Transactions on Magnetics, Sept 2000, v36, i5, p3670.

Xiang, W. , Huang, Y., and Majhi, S., The design of a wireless access for vehicular environment prototype for intelligent transportation system and vehicular infrastructure integration, Proceedings of IEEE 38th 2008-Fall Vehicular Technology Conference, 21-24 Sept. 2008, p.1-2.

Zalt, A.; Meganathan, V.; Yehia, S.; Abudayyeh, O.; and Abdel-Qader, I., Evaluating sensors for bridge health monitroing, Proceedings of IEEE EIT 2007 Proceedings, May 2007, p368(5).

Product datasheet for Wireless strain node SG-Link, 2009, available at www.microstrain.com

CC2420 datasheet http://focus.ti.com/docs/prod/folders/print/cc2420.html

Strain gage selection: Criteria, Procedures, Recommendations, 2007. Available at: http://www.vishaypg.com/docs/11055/tn505.pdf.