ABSTRACT
The introduction and development of wireless sensor network technology has resulted in rapid growth within the field of structural health monitoring (SHM), as the dramatic cable costs associated with instrumentation of large civil structures is potentially alleviated. Traditionally, condition assessment of bridge structures is accomplished through the use of either vibration measurements or strain sensing. One approach is through quantifying dynamic characteristics and mode shapes developed through the use of relatively dense arrays of accelerometers. Another widely utilized method of condition assessment is bridge load rating, which is enabled through the use of strain sensors. The Wireless Sensor Solution (WSS) developed specifically for diagnostic bridge monitoring provides a hybrid system that interfaces with both accelerometers and strain sensors to facilitate vibration-based bridge evaluation as well as load rating and static analysis on a universal platform.

This paper presents the development and testing of a wireless bridge monitoring system designed within the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University. The system interfaces with low-cost MEMS accelerometers using custom signal conditioning for amplification and filtering tailored to the spectrum of typical bridge vibrations, specifically from ambient excitation. Additionally, a signal conditioning and high resolution ADC interface is provided for strain gauge sensors. To permit compensation for the influence of temperature, thermistor-based temperature sensing is also enabled. In addition to the hardware description, this paper presents features of the software applications and host interface developed for flexible, user-friendly in-network control of and acquisition from the sensor nodes. The architecture of the software radio protocol is also discussed along with results of field deployments including relatively large-scale networks and throughput rates sufficient for bridge monitoring.

KEYWORDS: bridge monitoring, wireless sensor network, structural health monitoring, ambient vibration

INTRODUCTION
Monitoring of the nations transportation infrastructure using electro-mechanical sensors has long been proposed for complementing the current visual inspection program for condition assessment of bridges. However, the development of an application-oriented bridge management system for widespread utilization by national and state transportation agencies is a paramount task that currently necessitates further work in progressing not only measurement hardware and techniques, but also large-scale data processing algorithms and statistical methods. In particular, advancement in the field of structural health monitoring must address the shortcomings of early experimental programs and build upon the limited library of field-scale instrumentation studies, particularly those in which sufficient measurement histories are available both prior to and after progressively induced or natural damage occurs. In particular, assessment of earlier vibration-based instrumentation studies aimed at identifying prescribed damage to a bridge superstructure (Kato et al., 1986, Farrar et al., 1994) reveal either unsatisfactory low sampling rates or an insufficient number of sensors to reliably construct mode shapes for damage inference methods. More recent studies (Peters et al., 2001; Huth et al., 2004; Wenzel et al., 2005), have addressed the issue of limited number and density of sensors, as imposed by cost restrictions, using reference measurements. A larger grid is measured using a small number of sensors measuring grid points sequentially at different time histories and a reference sensor(s) at a fixed location is used to normalize the phase and amplitude. While this alleviates the hardware costs associated with the measurement system, sensors, and cabling, such an approach can not be utilized within the context of continuous monitoring and additionally results in a time-consuming process for short-term modal analysis, whereby test conditions must be assumed to remain constant during sequential tests.
Recently, there has been much interest in the use of wireless transceivers to transmit sensor data without the use of cables in order to address the costs and inconveniences of distributed cable-based sensor networks (Lynch and Loh, 2006). However, while the number of unique wireless sensor platforms has continued to rapidly expand, there has been limited success in replicating previous cable-based bridge assessment test programs in regards to the number of deployed sensors and data rates. However, while the number of unique wireless sensor platforms has continued to rapidly expand, there has been limited success in replicating previous cable-based bridge assessment test programs in regards to the number of deployed sensors and data rates. A review of recent wireless sensor deployments for structural health monitoring of bridges (Table 1) reveals that the networks have generally relied on either local data logging and post-sampling transmission of sensor data or on low sampling rates and/or limited numbers of sensors to achieve real-time transmission. For short-term monitoring, data logging may be an acceptable approach to ease the burden on the transceiver bandwidth limitation; however this architecture eliminates the possibility of sampling histories beyond several minutes and necessitates a much longer time period to recover the data across the wireless link. Additionally, reduced sampling rates may be acceptable for some bridges where there are many low natural frequencies, however moderately stiff and stiff bridges, such as integral abutment and short-span bridges, necessitate higher sampling rates to capture a sufficient number of modes for analysis. The system described in this paper has achieved higher sampling rates while maintaining reliable communication within a large, dense array of sensors.

Table 1. Survey of Real-time Wireless Bridge Monitoring Field Deployments

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Network Description</th>
<th>Data Delivery</th>
<th># of Sensors</th>
<th>Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pakzad, et al.</td>
<td>12 nodes log data from 3 channels over a sampling time of 4 minutes. Data is streamed after sampling resulting in a significantly more time consuming stage.</td>
<td>Post-sample delivery of logged data</td>
<td>36 Accel</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Paek, et al.</td>
<td>Five local networks of 4 nodes each with a single-board computer base station connected to an IEEE802.11b wireless radio.</td>
<td>Real-time</td>
<td>20 Tri-axis Accel</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Lynch, et al.</td>
<td>A wireless sensor network on a concrete box girder bridge alongside a wired system.</td>
<td>Real-time</td>
<td>14 Accel.</td>
<td>70 Hz</td>
</tr>
<tr>
<td>Current Study</td>
<td>A dense, multi-sensor wireless network on a single-span concrete deck on steel girder bridge</td>
<td>Real-time</td>
<td>29 Accel. 11 Strain</td>
<td>128 Hz</td>
</tr>
</tbody>
</table>

Naturally, short-term monitoring approaches concurrent to scheduled routine inspection have preceded the widespread deployment of permanent systems for continuous monitoring. This is consequent to the excessive costs and oversight associated with developing a distributed network of instrumented bridges, especially given that a definitive approach to identifying and localizing damage has yet to be formulated. Since an overwhelming number of bridges nationwide have approached or surpassed their service lifespan, it has become critical to allocate resources to the structures most in need of repair or replacement and consequently on-site bridge inspections have served as the primary means of identifying bridges in urgent need of repair or replacement. Short-term diagnostic testing through strain measurements from known truck load patterns has been utilized both independently and in conjunction with visual inspections for condition assessment (Wipf et al. 2003). This approach generally merges the results of the experimental strain analysis with codified analytical load rating measures to determine revised operating loads and ratings for the in-service bridge. The wireless bridge monitoring system developed in this study has been designed specifically as a tool to address the immediate needs of short-term monitoring through strain-based load rating with the advantage of complementary measurement of dynamic properties and modal analysis, while satisfying the anticipated needs of a concurrently developing distributed bridge management system for long-term vibration-based continuous monitoring.

WIRELESS SENSOR SOLUTION (WSS) FOR BRIDGE MONITORING
The wireless bridge monitoring system developed within the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University was designed as a universal platform for addressing the needs of monitoring systems for both load-ratings and vibration-based damage detection (Fig. 1). The design of the system hardware will be presented in addition to an overview of the embedded software application and host user interface.

**Fig. 1. Wireless Sensor Node with Strain Transducer and Dual-Axis Accelerometer**

**Wireless Transceiver Platform**

A wireless mote is a small circuit board generally consisting of a microcontroller and a RF transceiver, often with several peripheral devices for PC-based communication and data storage, which can be used to acquire and wirelessly transmit readings from analog or digital sensors, thereby incorporating the data acquisition at the site of the sensor and eliminating the need for often lengthy spans of cable to a host computer. Currently, many research and commercially available wireless transceiver platforms exist and therefore this study selected the platform deemed best suited by the authors for the requirements of the system rather than introducing another, likely redundant mote platform. The Tmote Sky wireless platform developed by researchers at the University of California at Berkeley and marketed by the MoteIV Corporation was selected based on consideration of onboard capabilities, power-consumption, and concurrent platform success with similar tasks. In particular, the three-channel direct memory access (DMA) controller and hardware multiplier onboard the MSP430 microcontroller were identified as highly desirable assets not generally found on most available platforms and proved to be essential for delivering the data rates achieved in the large-scale testing. The chip transceiver on the Tmote Sky operates in the 2.4GHZ frequency band with a maximum effective data rate of 250kbps and offers spread spectrum modulation for enhanced performance in this bandwidth of widespread use. The microcontroller is an ultra-low power model with an eight channel 12-bit analog-to-digital converter (ADC), a two channel 12-bit digital-to-analog converter (DAC), and two universal serial buses for communication with a variety of digital devices. The Tmote Sky motes are also compliant with U.S. and Canadian radio frequency regulations and are certified by the FCC and Industry Canada for use in either country.

**Accelerometer Signal Conditioning**

In order to facilitate high-resolution acquisition of distributed acceleration measurements for modal analysis of bridge structures, a custom signal conditioning circuit was developed to interface with the mote transceiver board. This section provides analog low-pass filtering, digital offset correction, and digitally programmable gain for up to two analog accelerometer signals. A 3V voltage reference is used to provide ultra-low noise, stable power supply to the accelerometers and filter sections. The analog filters have a 100Hz frequency cut-off with a Butterworth response and are provided to prevent signal aliasing. Each filter is a 5-pole Sallen-Key design featuring dual second-order sections on the conditioning board and a real-pole section provided within the external accelerometer. Placement of the real-pole filter with a buffer amplifier enables greater noise-immunity through low-impedance output at the signal source and permits the use of other MEMS accelerometers, which generally have different resistance on the signal output.

The low-noise, low-power LT6915 programmable gain amplifier was selected for providing amplification of the sensor signal to maximize the resolution of the conversion specific to the on-site vibration amplitude. In-network commands enable adjustment of the gain from zero up to 4096V/V in binary multiples. Independent non-volatile programmable voltage references set through the use of the 12-bit DAC on the microcontroller are used to digitally
correct the gravitational offset of each channel within 1mV. This adjusts the sensor input range such that it is balanced in both the positive and negative directions and permits the use of high gain amplification without driving the signal out of range. A 1.25V reference is provided to bias the amplifier output to the mid-span of the ADC conversion range, which is set with a 2.5V external voltage reference. Hardware shutdown of the PGA and voltage reference supply to the accelerometer and filter sections conserves limited battery resources during periods of inactivity.

An over-sampling approach is taken in the acquisition of accelerometer measurements in order to increase the effective resolution of the ADC conversion through reducing the quantization noise as well as to virtually eliminate signal attenuation in the measured bandwidth. A customizable and remotely programmable digital filter is implemented using the hardware multiplier within the MSP430 microcontroller. Sensor data is over-sampled by a user-specified rate and then passed through the digital filter prior to down-sampling to the effective data rate that is transmitted across the radio. The use of over-sampling reduces the effect of ADC quantization noise and is generally accepted to provide an additional bit of effective resolution for each power of four rate of over-sampling. The over-sampling also satisfies the anti-aliasing criteria of the analog low-pass filter. The cutoff frequency of the analog filter was deliberately set higher than the anticipated measured bandwidth due to the relatively poor roll-off characteristics of this analog filter. The use of a high-order digital filter with a cutoff frequency in the pass-band of the analog filter eliminates aliasing from higher frequencies and results in a much tighter transition-band with virtually no signal attenuation for the majority of the measured bandwidth (Fig. 2).

The LIS2L02AL capacitance-based MEMS accelerometer manufactured by ST Microelectronics has been selected for its low-power consumption, ultra-low noise floor, and low-cost. This dual-axis accelerometer has a 30 $\mu g/\sqrt{Hz}$ noise density with a white-noise distribution, permitting resolution below $240 \mu g$ for a 64Hz input bandwidth. These accelerometers were mounted on custom printed circuit boards containing the real-pole section of the analog filter. The boards are encased in potting epoxy within a small external housing to maintain the high resonant frequency of the sensor and enable direct placement of the sensor on the structure for superior vibration transfer. A short length of cable terminated with a water-tight industrial connector links the sensor to the wireless sensor conditioner and transceiver unit.

**Strain-Transducer Signal Conditioning**

Load rating is a widely accepted short-term measurement task that utilizes a large array of strain transducers for measurements of the induced strains and strain profiles to known loads in order to calculate neutral axis locations, distribution factors, end fixity and ultimately rated loads for a bridge. In order to facilitate this task using a wireless sensor network to significantly reduce the field deployment time, an independent signal conditioning interface was also incorporated into the sensor node design for full-bridge transducers. The core of this circuit is the ZMD31050 application specific integrated circuit (ASIC) designed specifically for the conditioning and acquisition of full-bridge sensor measurements. This chip features 13 stages of programmable gain up to 420V/V, digitally programmable analog offset nulling, and a 15-bit internal ADC with adjustable input range to maximize the range of the signal over the ADC range. In addition, signal inputs are provided for either temperature diode or thermistor-based temperature measurement. An internal microcontroller introduces a digital conditioning algorithm for linearization of the sensor signal as well as providing up to $2^{nd}$-order polynomial temperature compensation using the external sensor. Temperature compensation is a critical correction for long duration strain measurements using
strain transducers, as the temperature-induced expansion of bridge elements often differs with temperature-induced transducer expansion, thereby resulting in a strain output in the absence of applied deck load. This signal conditioning ASIC communicates digitally with the mote’s microcontroller through the use of the 2-wire serial (I2C) interface. A voltage regulator is used to provide a low-noise, regulated supply to the external transducer and signal conditioning chip as well as to enable digitally controlled hardware shutdown for power conservation during periods of inactivity.

For field testing and system validation, reusable strain transducers marketed by Bridge Diagnostics Incorporated (BDI) were selected, as these have been widely utilized for bridge load ratings nationwide. These sensors have a gauge length of 76.2mm (3in) and are housed within a sealed stainless steel case. Sensors are applied to bridge elements using threaded mounting tabs that are adhered to surfaces with high-grade epoxy. The factory length of cable was terminated with a water-tight industrial connector for linking to the wireless sensor node.

Software

Embedded software applications were written for both the remote and base wireless transceivers under the TinyOS-1.x open source operating system. While the TinyOS framework and the accompanying assembler code were utilized for programming the motes, the software modules and interfaces were generally found to be incompatible with the requirements of the monitoring task and therefore seldom used. Extensive development of low-level software enabled much higher data throughput, a greater number of nodes per network while maintaining reliable transmission, and other advanced features, such as digital filtering with the hardware multiplier. The embedded software was designed to balance efficiency and throughput with flexibility, so that the same code could be utilized for an array of monitoring tasks and sensor network configurations.

A highly developed LabVIEW host application has been written to operate in conjunction with the remote transceivers to control and coordinate the wireless network. The LabVIEW software establishes bi-directional communication with a base mote through a USB connection operating at 262,144 baud. A user-friendly interface permits programming of sampling rate, duration of sampling, sampling initiation, component power supply status, and configuration of individual signal conditioning circuits. Sensor nodes can be individually programmed to sample in several configurations: two channels of accelerometer data, one channel of each accelerometer channel and the strain channel, or simply the strain channel. This permits the multi-functional nodes to perform only the tasks specific to the current monitoring program and sensor layout. Programmable gain for the accelerometer channels is selected on a per channel basis, while the embedded software handles automatic adjustment of the sensor offset to the mid-span of the signal range. This enables rapid sensor configuration with minimal operator commands and discretion. An extensive digital filter design sub-section of the host software allows the operator to design a custom filter, the coefficients of which can be transmitted to the nodes wirelessly over the network. In addition, network status can be queried through a single command that reports the status of the component power supplies, regulated mote supply voltage, and received signal strength. Upon initiation of sensor sampling, the host software receives incoming data packets, displays the measurements in real-time on a series of waveform charts, and logs the readings to individual spreadsheet files for post-processing.

RADIO TRANSMISSION PROTOCOL

In order for wireless sensors to be an effective alternative to cable-based instrumentation for bridge monitoring tasks, the network capabilities must at the least permit replication of the number of deployed sensors as well as the sampling rates utilized in traditional field tests. The use of a bidirectional, intelligent, and coordinated radio transmission protocol is essential for reliable data reception in a large sensor array operating with high data throughput. The protocol developed (Fig. 3) and described below has been found to support up to 40 channels of sensor data with per channel sampling rates of up to 128sp/s in a single network, which is comparable to, if not beyond, the instrumentation setup of most cable-based bridge vibration monitoring studies. This system-level success signals that the use of wireless sensor networks for structural health monitoring should no longer be regarded as wishful thinking, but accepted as a currently feasible and economic approach.

In order to facilitate concurrent communication with a high-volume of deployed sensor nodes, scheduling of packet transmission was found to be essential to prevent significant packet loss from collisions. The protocol implemented assigns a sequential time offset between packet transmissions based on the local address of the node. This, however, does not mean that sampling between nodes is offset; all nodes initiate sampling simultaneously as triggered by a single command from the base node. The nodes utilize the first-in-first-out transmission buffer onboard the chip.
transceiver to temporarily hold the packet to be transmitted until the time window scheduled for transmission occurs. To additionally ensure that packet collision rarely occurs, if ever, the clear channel assessment feature of the chip transceiver is utilized, whereby the packet is only transmitted if the measured received signal strength is below a threshold value and no IEEE802.15.4 data is being transmitted across the current channel.

Despite local transceiver scheduling, there is no guarantee that transmissions will be received at the base node and without bit errors. Consequently, all data packets request an acknowledgement packet from the host, which is returned only in the even that the packet is received and passes the cyclic-redundancy error checking. This bidirectional mode of data transfer from the remote nodes provides the local node with the opportunity to implement a means of retransmission for complete data recovery. The transmission schedule developed provides an additional time slot for retransmission of packets failing to receive an acknowledgement of host reception. In the event that the retransmission also fails to receive an acknowledgement, the complete data packet is transferred to a transmission queue for retransmission during available radio access time. These instants of availability occur during the local node scheduled time for retransmission of packets failing to receive acknowledgement on the first attempt, if the previous packet was successfully acknowledged, or at the conclusion of the data sampling. During system validation, the transmission queue rarely contained more than a few packets and any packets transmitted at the conclusion of sampling were generally from the last seconds of the sampling duration.

![Fig. 3. Radio Transmission Protocol Flow Chart](image)

**SYSTEM LEVEL VALIDATION**

Thorough laboratory validation tests, as well as field deployments, have been undertaken to evaluate the performance of the developed wireless bridge monitoring hardware platform as well as the embedded software and radio transmission protocol. The scope of laboratory testing included spectral verification of accelerometer sensors, time synchronization verification of independent nodes, investigation of effective packet success rate, and multi-axis modal analysis of a laboratory scale bridge. A large-scale, high-rate field deployment on a single-span bridge served to further verify the system capabilities for a real-world application (Whelan, et al., submitted).

A Polytec scanning laser vibrometer was used to verify the acceleration spectra recorded by the wireless sensor nodes due to sinusoidal and sine-sweep inputs from a small shaker (Fig. 4). A sequence of small amplitude tests was performed over a range of excitation frequencies using an accelerometer sampling rate of 256Hz. Comparison
of the laser vibrometer spectrum with the accelerometer spectrum yielded exceptional correlation for both the amplitudes and frequencies of the signals. Consequent to this comparison with state-of-the-art instrumentation benchmark measurements, the transfer function of the wireless node hardware and software as well as the accuracy and stability of the sampling clock can be deemed valid. Synchronous sampling initiation and data collection was verified through placement of several sensors on a single shaker with a low-frequency sinusoidal input. Waveforms from independent sensor nodes overlapped in phase with the only small amplitude deviations due to sensor noise and small discrepancies in orientation and placement. While no explicit time synchronization scheme is employed in the embedded software to date, the individual sampling clocks are created with accurate 32kHz crystal oscillators. Any clock drift between nodes is small enough that no significant phase difference is created in reference to the frequencies measured for the structural response. Clock drift was not found to affect the performance of the radio transmission protocol and scheduled transmission slots for the short-term monitoring employed in laboratory and field tests.

Summary of Field Deployment Statistics
A large-scale network consisting of 40 channels of sensor measurements acquired through 20 remote wireless transceiver nodes was deployed on an integral abutment, single-span bridge in St. Lawrence County, NY (Fig. 5). The bridge is a 17.07 m (56ft) span reinforced concrete deck on four steel girders spaced 2.74 m (9 ft) center-to-center. Both quasi-static, similar to load-rating protocol, and dynamic monitoring of the bridge was conducted using a total of 29 accelerometers and 11 BDI strain transducers. Only ambient loading from vehicular traffic was provided for structural excitation. Each channel of sensor data was over-sampled at 512Hz, passed through a 55-tap digital low-pass filter, and decimated to an effective sampling rate of 128Hz for real-time transmission to the host computer. This network configuration and sampling rate resulted in a transmission overhead in the range of 97kbps to 126kbps depending on the initial packet success and retransmission rates.
The average packet success rate across all of the sensor nodes over ten 3 minute test cycles was 99.91%, with 92% of the nodes reporting 100% packet delivery success. The minimum packet success rate over these tests was 98.0% (Fig. 6). The small loss of data is attributed to a software bug in the portion of the code responsible for transmitting any packets in the transmission queue after sampling was completed. It is anticipated that correction of the software section responsible for transmitting packets remaining in the queue will result in complete data sets; however at the current level of packet success over the sampling time, the system identification analysis suffered from no noticeable or adverse distortion. This degree of transmission reliability at the high data throughput rate attained in this testing reveals that wireless sensor networks are currently capable of performing large-scale structural health monitoring tasks with real-time transmission.

![Fig. 6. Histogram of packet success rates over field deployment testing](image)

The integral abutment bridge design was beneficial for investigation of the sensor performance on a full-size structure, as the relatively high stiffness created a demanding measurement scenario. Peak accelerations from vehicle loading ranged from less than 2mg to only nearly 10mg. However, the sensors, which were amplified either by 64V/V or 128V/V depending on location from the abutments, provided clear representations of the time-history data and distinct peaks within the frequency spectra, even with only ambient loading (Fig. 7). The exceptional system performance with such low excitation levels on a relatively stiff structure implies even enhanced measurements on longer-span structures with lower natural frequencies.

![Fig. 7. Average normalized power spectrum across all vertical acceleration channels from a single 186 second duration ambient vibration test](image)

Strain measurements also verified high-quality performance, despite significantly lower applied loads than typically imposed during a scheduled load rating. The development of bending strain in the girders during a crawl-speed pass of a large sports utility vehicle was well captured at most locations (Fig. 8). The localized tension spike recorded at the top of the girder occurs when the vehicle wheel is directly overhead the sensor. However applied loading was not sufficient to induce significant enough strains to deem the near-abutment measurements valid within the manufacturer specifications. During a typical load rating, much larger vehicles with additional loads would be
utilized and such an issue would not occur. Strain profiles were found to be consistent with vehicle loading patterns, composite action of the deck and girders was verified, and calculated neutral axes locations correlated well with theoretical calculations.

![Strain response at top and bottom flange at midspan of girder during light vehicle pass](image)

**Fig. 8.** Strain response at top and bottom flange at midspan of girder during light vehicle pass

System identification through both classical peak-picking as well as stochastic subspace identification (SSI) methods was used to analyze the vibration data using the commercial software package, Modal Analysis of Civil Engineering Constructions (MACEC) (Van den Branden, 1999). The experimental mode shapes (Fig. 9) and natural frequencies were found to correlate well with a finite element model developed from as-built drawings and analyzed using the ALGOR software package.

![Mode shapes](image)

**Fig. 9.** First 9 experimental mode shapes in the vertical axes (surface is a cubic-spline interpolation; data points are super-imposed as circles)
CONCLUSION
A multi-functional wireless bridge monitoring system has been developed for concurrent deployment of accelerometers, strain transducers, and temperature sensors. The hybrid sensing capabilities of these nodes satisfy the immediate requirements for economic, low-maintenance load ratings and short-term dynamic measurements in addition to providing the hardware functionality for development of a long-term continuous bridge monitoring system. Extensive laboratory and field testing and development has been performed to produce a reliable radio transmission protocol capable of sustaining a large number of nodes with high data throughput in real-time. Field deployments have verified the ability of the system to capture natural frequencies and construct clear modes shapes even for a relatively stiff bridge. The ability of this wireless sensor network to replicate the performance of cable-based deployments, in terms of number of sensors and sampling rates as well as successful data analysis, signals a breakthrough in wireless sensor network development. Such emerging technology is now capable of performing the bridge monitoring tasks that have been highly proposed and promised, though seldom demonstrated.

ACKNOWLEDGEMENTS

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