
T. Harms\textsuperscript{a}, B. Banks\textsuperscript{a}, S. Sedigh Sarvestani\textsuperscript{a}, and F. Bastianini\textsuperscript{b}

\textsuperscript{a}Department of Electrical and Computer Engineering
\textsuperscript{b}Center for Infrastructure Engineering Studies
Missouri University of Science and Technology, USA

ABSTRACT
This paper describes the design and testing of a wireless sensor network based on the SmartBrick, a low-power SHM device developed by the authors. The SmartBrick serves as the base station for the network, which utilizes additional sensor nodes to periodically evaluate the condition of the structure. Each node measures vibration, tilt, humidity, and strain, and is designed for easy interfacing of virtually any other analog or digital sensor. The sensor nodes use Zigbee to transmit their data to the base station, which in turn uses the GSM cellular phone network to provide long-range communication and support for remote control.

The system has been designed from the outset to minimize power consumption, and is projected to operate autonomously for up to four years without any on-site maintenance, due largely to the minimal power consumption and rugged design. Remote calibration over the GSM network further increases the autonomy of the system. Most importantly, it can perform all requisite actions with no cables for power or communication. The focus of this paper is the addition of short-range wireless communication over Zigbee. This allows a network of several devices to be used to monitor larger structures, such as multi-span bridges. Results of laboratory testing are included and discussed in detail, demonstrating the unique capabilities of the proposed SHM system.

Keywords: structural health monitoring, wireless, sensors, Zigbee.

1. INTRODUCTION
In recent years, safety of the transportation infrastructure has become an increasing concern in the United States and worldwide. As the infrastructure ages, not only do roads and bridges deteriorate naturally, but their utilization increases as populations grow in size and mobility. This structural degradation can pose major safety hazards, especially on structures such as bridges. According to the US Federal Highway administration, over 25% of the bridges in the United States are either structurally deficient or functionally obsolete.\textsuperscript{1} It is important to take action and better assess the condition of civil structures to improve the safety of the transportation infrastructure. Especially in the face of the recent economic downturn, the high cost of traditional structural evaluation methods is significantly less attractive from a financial perspective. Structural evaluations require the evaluator to be on-site, which requires extensive travel and leads to under-utilization of the evaluator’s time and an increase in costs. For these reasons, a significant amount of research has been focused on developing low-cost, low-power, robust devices to monitor the health of transportation structures.

Structural health monitoring (SHM) systems have shown great potential to improve infrastructure safety, and can provide significant additional information regarding the condition of a structure. Several wired SHM systems have been developed, but many suffer from high cost, inadequate design, complex installation, or some combination of these shortcomings. They are highly reliable provided that the structure has adequate power. These systems take advantage of proven technologies such as commercial real-time data acquisition systems. However, wired sensors distributed around a structure necessarily require large amounts of wiring to monitor the structure. This makes these systems difficult to retrofit on existing structures, limiting installation to new bridges, which hampers utility with respect to improving safety of an infrastructure that is already in-place.
In order to address the high cost and complex installation associated with wired SHM systems, several low-power wireless systems have been developed. The majority of these systems are unsuitable for long-term installation on a structure for a variety of reasons. Many of these systems have insufficient data storage capabilities, high power consumption, or inadequate enclosures. These design issues all contribute to a reduced field life and a need for frequent site visits for system maintenance, which eliminates many of the benefits of using a wireless SHM system. While the sensing operations are generally performed by low-power wireless nodes, data is often aggregated and processed by a laptop computer on-site, which offers virtually unlimited storage and can provide remote access, but has exorbitant power requirements and is virtually impossible to power without mains power on-site.

To overcome the issues associated with many existing wireless SHM systems, we have developed the SmartBrick, which is a completely wireless, fully autonomous system for SHM. The SmartBrick, which has been previously presented by the authors,\textsuperscript{2,3} offers extensive SHM capabilities. It is capable of measuring environmental and structural phenomena such as temperature, strain, tilt, and vibration. It has extensive I/O and several expansion headers, allowing the system to function with virtually any analog or digital sensor, as well as optional control of external devices such as actuators. Possibly the most important feature of the SmartBrick is that it is equipped with a quad-Band GSM/GPRS modem, which allows it to operate completely wirelessly while providing full remote monitoring, maintenance, and calibration features. The SmartBrick can operate in any location where there is an available GSM network, which allows it to be used virtually anywhere in the world without requiring special equipment. In addition to its monitoring capabilities, the SmartBrick can generate alerts and send them to authorities or the local public via SMS text message or e-mail. The SmartBrick is capable of two-way communication over the cellular network, which offers remote calibration and upgrades, and enables all data to be uploaded autonomously using a combination of FTP, text message, and e-mail.

2. RELATED WORK

Several existing structural health monitoring projects use wireless communication to facilitate coordination of devices for more effective measurement of a structure, whether the goal is improved spatial resolution, network resilience, or advanced in-situ analysis. The majority of these systems\textsuperscript{4–12} are based on general-purpose sensing platforms or motes, which provide basic sensing functionality but are largely unsuited for long-term installation on civil structures. These commercial network devices greatly reduce development time, as little, if any, hardware design is required. It is then possible to spend more time developing and optimizing software to attain basic functionality immediately and gradually improve the system wherever possible. Most of these systems suffer from high power consumption and are generally equipped with a small power supply. Even under the most extreme power management circumstances, these motes have an unattended life of approximately one year. These motes are also limited in the number of I/O connections available for sensors, meaning that many motes are necessary if more than a few temporal data points are needed. Almost all of these systems use a laptop or base station to aggregate data from the sensor nodes, and the networks have virtually no mechanism for remotely communicating the measured data without available mains power and costly wired or wireless communication hardware. This restricts the number of potential installation locations, as many bridges, especially in rural areas, do not have power available on-site.

Although most of these structural health monitoring systems use Zigbee, which is ideal for low-power, low-data rate communications, a few projects employ Bluetooth\textsuperscript{13} or Wi-Fi\textsuperscript{14} to communicate within the network. Both technologies work in the same frequency range and provide better data throughput than Zigbee, at the cost of much higher power consumption. This is acceptable in some sensing applications, e.g., high-frequency vibrational analysis, but is rarely justifiable for sensor networks.

Several projects described in the literature, e.g.,\textsuperscript{15–18} utilize hardware specifically developed for SHM. The authors of these studies have summarily demonstrated the effectiveness of wireless sensor networks for SHM, but the systems are not described as being intended for extended operations in the field. Power consumption is still high, but not as high as systems using motes. With the exception of,\textsuperscript{17} which is reported to yield a battery life of five years, none of the aforementioned systems is designed for continuous operation of more than a year.
3. IMPLEMENTATION
As described in previous publications,\textsuperscript{2,3} the SmartBrick hardware has been designed from the ground up to provide an effective, low-cost, low-power solution for structural health monitoring. It has several onboard sensors for phenomena such as temperature, tilt, and vibration, can be connected to external sensors to measure strain, load, water level, and can interface to virtually any analog or digital sensor. It is intended to provide years of unattended monitoring, reducing the need for on-site maintenance or inspection through remote calibration and upgrade mechanisms. The hardware has several analog inputs and a suite of digital communications capabilities, including RS232, RS485, and SPI, which are pervasive in electronic devices and allow the SmartBrick to work with numerous external components.

The SmartBrick hardware, depicted in Figure 1 is now in its third generation, with several improvements since the second generation prototype. Most notably, decreased power consumption provides extended field life, and a denser board layout and integrated inputs for common sensors such as strain gages eliminate the need for expansion boards for basic sensing functionality. An integrated LCD and extended I/O connectors provide more control and versatility over previous SmartBrick devices. The new revision has improved screw terminals for connection of external sensors and fits in the same IP-68-compliant enclosure. The hardware also supports three separate power sources, which enables use of a combination of rechargeable or alkaline batteries and a renewable energy source such as a solar panel to extend field life and provide greater versatility and reliability with respect to device power.

Since extensibility was one of the major goals of the SmartBrick, incorporating additional communications, storage, or measurement technologies is possible without requiring modification to the base hardware. Taking advantage of this feature, an 802.15.4/Zigbee radio has been added as a small expansion board to the SmartBrick system. This board is based on a Texas Instruments CC2480 Zigbee Network Processor. This particular device is one of very few available parts that handle virtually all network-related tasks without consuming more of the limited computing power of the host device. More importantly, this feature enables a very clean separation between the network and monitoring responsibilities of the device.

The CC2480 is a versatile device with a well-defined API that provides all necessary functions for implementation of a full-featured Zigbee interface. In addition to supporting multiple host software configurations, it can be added to systems with either UART or SPI hardware interfaces, providing greater flexibility in hardware designs. The software developed for controlling the CC2480 is intended to be easily portable to later SmartBrick devices, even if the physical interface changes. The CC2480 is a relatively low-power part, as it consumes approximately
81 mW of power at maximum. This low power consumption is ideal for remote monitoring applications such as the SmartBrick system, which has a very limited power supply and stringent field life requirements.

For this incarnation of the Zigbee expansion board, the ez430-rf2480 development kit was used as a starting point for integration of the CC2480 into the SmartBrick system. This development kit enables rapid prototyping without requiring extensive design, layout, and assembly of the transceiver boards. It allows test programs to be written on multiple host platforms to gain familiarity with the software interface and timing requirements. There are, however, some drawbacks to using these pre-assembled modules. Foremost, the evaluation modules are intended to operate in a standalone fashion, and are therefore difficult to control from a separate device, despite an available physical interface. The evaluation modules consume more energy than the transceiver alone, and are limited in their transmission rates, which translates to an overall reduction in system data throughput.

The CC2480 itself requires very few external parts, and even the evaluation module has fewer than 40 components. This minimizes the cost of construction and integration into the SmartBrick hardware. Aside from the transceiver itself, which costs approximately $11 per unit in large quantities, there is virtually no additional cost from components. PCB fabrication and assembly will add significantly to the prototype cost, but in large quantities becomes quite manageable.

In terms of software design, the interface for handling Zigbee network traffic is straightforward, although integrating it with the SmartBrick operating system without disturbing the sensing and monitoring responsibilities requires some care. Most importantly, the short-range communications should not exclusively control the processor for extended periods, preventing scheduled operations from occurring at proper intervals. To achieve this, the software is written to asynchronously handle events from the network processor and use the operating system’s task scheduler to service network events whenever the processor is not running a higher-priority operation. All sensing operations take priority over short-range wireless communication, should any conflict arise.

The host software implements the “Simple API” interface for the CC2480 device. This provides all of the necessary function to establish a basic Zigbee wireless sensor network. The CC2480 also provides an extended interface, which provides advanced networking capabilities. This extended interface is currently being incorporated into the SmartBrick operating system to enable greater versatility and compatibility with other Zigbee devices. Aside from the obvious objective of providing a reliable short-range wireless communication interface, a major design goal in integration of this API is to keep the software portable. This will allow simple integration into future SmartBrick devices, and potential expansion to a broad range of projects.

It should be noted that this approach is different from that presented by the authors in. Originally, the Texas Instruments CC2430 was used as a coprocessor handling all of the network-related tasks and enabling the host controller to focus on measurement and monitoring tasks. The previous approach provided high data throughput, but extended control of the Zigbee network was particularly difficult without a well-defined interface, and software development on the CC2430 proved particularly challenging. The major limitations encountered with the previous approach were a limit on the number of devices that could be effectively monitored, difficulty controlling more than the most basic network functions, and high sleep power consumption. The CC2480 device consumes equal power in active (Transmit/Receive) modes as the 2430, but has a lower sleep current and provides a full Zigbee interface to the host controller. With these challenges and the recent availability of a new part that was almost exactly a drop-in replacement in terms of interface and physical construction, development of a master-slave interface to the CC2430 device was discontinued.

There were several major challenges in implementing the necessary software components to control the transceiver using the SmartBrick. The most significant issue was related to the timing of commands to the evaluation module. Since the evaluation module is actually comprised of a secondary microcontroller that issues commands to the transceiver, some of the features available on the transceiver itself are not easily translated to the host controller. In essence, the secondary controller would time out waiting for large commands to be issued from the host controller, despite operating at a supported baud rate. This behavior is undocumented and virtually undetectable on the target board, as it gives no indication whenever a command is corrupted or incomplete. This limitation is specifically related to the use of the evaluation module, and should have no effect on the final hardware.
While the transceiver itself supports high-speed communication with a host microcontroller, the evaluation module is limited in its maximum supported UART baud rate. This creates a bottleneck, again, in the secondary microcontroller. The alternative, in this implementation, is to not wait for the synchronous response of the transceiver. Response times of the transceiver to commands from the host often exceed one second, which drastically reduces the effectiveness of the evaluation module as a link to other local devices. Commands and requests from the transceiver to the host are processed dramatically faster, which allows the host to handle data from a large number of wireless nodes despite its limited transmission speeds.

Despite the aforementioned shortcomings, the evaluation modules were very effective in assisting in the implementation of necessary software routines to communicate with the CC2480 network processor. The development time saved by avoiding PCB design and assembly was significant, and the project is prepared to move forward with a new hardware design based on this versatile network device.

These hardware and software design features facilitate simple, reliable communication and coordination between SmartBrick devices. This enables the use of multiple heterogeneous nodes for monitoring larger structures with a greater number of sensors than possible with a single SmartBrick node. The choice of using the Zigbee communication protocol instead of one of the many 802.15.4-based proprietary protocols allows the SmartBrick system to interoperate with third-party Zigbee-enabled devices.

4. PERFORMANCE AND LABORATORY TESTING

In order to test the wireless functionality of the SmartBrick system with the CC2480 evaluation module, several sensor boards were placed in the perimeter of a laboratory area and reported temperature measurements to the SmartBrick. The SmartBrick was configured to interact with the wireless module over UART, which is the only interface available without requiring modifications to the module. The UART was set to 38.4 kbps, which is the empirical maximum for reliable communication of the SmartBrick and the evaluation module. The SmartBrick then configured the module as a coordinator and registered its application profile on the network, enabling the sensor boards to connect to it and report their measurements.

The sensor boards reported the measured temperature once every ten seconds, and the devices were moved to several locations to evaluate the range and resiliency of the wireless devices in an electromagnetically noisy environment. Transmission range is somewhat limited due to the small PCB antenna used on the evaluation modules. Additionally, a Texas Instruments CC2430DB was used as a packet sniffer in the immediate vicinity of the coordinator to verify the network traffic and monitor noise levels and timing. The SmartBrick was
able to consistently and reliably receive and process sensor readings from the evaluation modules at a range of up to 15 meters, despite several electromagnetic obstacles, such as cinder block walls (preventing line-of-sight transmission) and several wireless computers in the same frequency range. The evaluation modules are optimized for size, rather than wireless performance, and have a shorter antenna than will be on the final hardware, which means that transmission reliability and range should both improve with the final hardware.

With explicit acknowledgement protocols, data transmission was limited to approximately 100 bytes per second. This is due to the limitations of the evaluation module specifically, and greater transmission rates can be achieved using the CC2480. For example, if restrictions are lifted on waiting for the device to respond over UART, a transmission rate of 2000 user bytes per second can be achieved. Using the improved SPI interface of the transceiver should enable transmission rates well beyond these, should the need arise. For the typical sensing applications of the SmartBrick, relatively small amounts of data are collected and even the lowest of transmission rates can be useful. However, as the project expands to include more extensive acceleration data and vibrational analysis, higher data rates will be required.

The evaluation module, which is comprised of the CC2480, an ultra-low power MSP430 microcontroller, and a few external components, drew only marginally more power than specified for the CC2480 alone. The current draw at 3.0 volts was 34 mA for the entire device in active (transmit/receive) modes, which is comparable to other Zigbee network processors. The transceiver, according to specifications, draws a maximum of 27 mA in active mode. This value was corroborated by the data gathered. The addition of the transceiver does, however, incur an almost twofold increase in the power consumption of the SmartBrick when the processor and network hardware are fully active. Since the device spends most of its time in sleep mode, and not communicating, it is easy to take advantage of the SmartBrick’s power conservation mechanisms and completely disconnect the transceiver if needed. Based on a one-minute-per-day communication cycle, which is enough to transmit several kilobytes of data, even with the evaluation module, the SmartBrick has a viable field life of approximately four years, depending on configuration and communication patterns.

5. PLANNED FIELD TEST

The original SmartBrick field test began in November 2006, which highlighted many features of the system, but also a few shortcomings. A second, three-year field test was originally scheduled to begin in Fall 2008, but has been postponed due to economic constraints that have delayed construction of the bridge chosen as the test site. The bridge, when constructed, will use several different types of pre-cast slabs to form the structure and bridge decks. This provides an excellent opportunity to test both the SmartBrick system and the benefits of this type of construction. Sensors embedded in the concrete will facilitate validation of a portion of the data collected by the SmartBrick system.

The field test will incorporate at least eight SmartBrick nodes to monitor over 50 strain gages placed along rebar in the structure. Additionally, several accelerometers and temperature sensors will be installed on the bridge to achieve an improved perspective on the bridge environment. The proposed sensor placement is shown in Figure 3. Sensors will be placed throughout the structure, at various heights and depths. Due to the bridge’s unique construction, the measurements are intended to provide information on the behavior of the individual structural components, as opposed to the structure as a whole. The symmetry and pre-fabricated nature of the structure is exploited so that several sensors can be placed on one of many similar members and reduce the number of sensors required to assess the bridge.

6. CONCLUSIONS AND FUTURE WORK

The SmartBrick system continues to expand in capabilities and performance. The system now has reliable means of communication with other devices in the vicinity, and even with the limited capabilities of the ez430-RF2480 evaluation modules, can sustain data rates sufficient for the SmartBrick system to report all of its measurements with a minor increase in overall power consumption. Testing demonstrated that the CC2480 network processor is a good fit for the SmartBrick system, as the extra processing overhead incurred is extremely small compared to previous efforts. In addition, the software is simpler to implement and maintain, and does not require exclusive
control over device operations, which leaves the SmartBrick free to continue normal operation, but with the added benefit of short-range communication.

Field testing of the device has been temporarily suspended, due to economic constraints that have delayed construction of the bridge selected as the test site. When construction of the bridge, located in Washington County, MO, is complete, a three-year field test of the SmartBrick system will be carried out. This is the primary goal for the near future. Additionally, given the promising results of integration of the CC2480 device, dedicated hardware will be produced, which should show dramatic improvements in wireless reliability, range, and throughput, while providing a marginal reduction in power consumption. A smaller, lower-power node is also in development, which will round out the necessary SmartBrick components for full-scale implementation on large structures. In the slightly longer term, a full-featured web interface is in development to allow straightforward calibration and access to data logs by users via the internet. The SmartBrick system remains one of the most reliable, durable systems for long-term structural health monitoring and carries the potential to dramatically increase public safety via SHM.

7. ACKNOWLEDGMENTS

This research was funded in part by the Missouri S&T Intelligent Systems Center.

REFERENCES


