Frequency Agile Wireless Sensor Networks

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ABSTRACT

Our goal was to demonstrate a wireless communications system capable of simultaneous, high speed data communications from a variety of sensors. We have previously reported on the design and application of 2 KHz data logging transceiver nodes, however, only one node may stream data at a time, since all nodes on the network use the same communications frequency. To overcome these limitations, second generation data logging transceivers were developed with software programmable radio frequency (RF) communications. Each node contains on-board memory (2 Mbytes), sensor excitation, instrumentation amplifiers with programmable gains & offsets, multiplexer, 16 bit A/D converter, microcontroller, and frequency agile, bi-directional, frequency shift keyed (FSK) RF serial data link. These systems are capable of continuous data transmission from 26 distinct nodes (902-928 MHz band, 75 kbaud).

The system was demonstrated in a compelling structural monitoring application. The National Parks Service requested a means for continual monitoring and recording of sensor data from the Liberty Bell during a move to a new location (Philadelphia, October 2003). Three distinct, frequency agile, wireless sensing nodes were used to detect visible crack shear/opening micromotions, triaxial accelerations, and hairline crack tip strains. The wireless sensors proved to be useful in protecting the Liberty Bell.

Keywords: RF, wireless, transceiver, sensor, accelerometer, strain gauge

1. INTRODUCTION

Wireless sensor networks represent an enabling technology for the next generation of structural health monitoring systems and smart structures. The ability to move data from multiple sensing nodes on a structure or machine to wide area networks and to the internet could provide great benefits. These include improved condition based maintenance, fewer equipment failures, enhanced productivity, improved security, more efficient use of human and natural resources. Furthermore, the elimination of lead wires provides significant cost savings as well as creating improved reliability for many long term monitoring applications.

We have previously reported on addressable, data logging wireless sensor nodes capable of fast (2K sample/sec/channel) data rates[i]. These systems were designed to tightly control the flow of data from sensor nodes to base station. This control was required to prevent nodes from interfering with one another, due to a limited number of available radio frequency (RF) bands, particularly for applications where time division multiple access (TDMA) could not support the data rates (1 to 2 samples/sec/channel) required for many measurement applications[ii]. To control data flow, the base station requests that a specific addressable node on the network log, send, or stream wireless data, then, on receiving these commands, the specified addressable node responds.

However, many structural measurement and machine control applications require that strain; acceleration, torque, force, pressure, and temperature measurements are made at high data rates and in real time. This requirement is driven by the need to protect valuable process equipment from overloads, or to help research engineers to better visualize and interact with the system under test. Ideally, a distributed network could be deployed over the structure

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or machine, and the network would consist of multiple, smart, independent, and fast wireless sensing nodes, each node capable of simultaneous RF communication.

2. OBJECTIVE

To demonstrate a wireless sensor network capable of simultaneous, high speed data acquisition from distributed, programmable, multichannel sensing nodes, these nodes capable of handling a wide variety of sensors.

3. METHODOLOGY

A functional block diagram of a versatile wireless sensing node is provided in Figure 1, below. A modular design approach provides a flexible and versatile platform to address the needs of a variety of applications[iii], [iv]. For example, depending on the sensors deployed, the signal conditioning block can be re-programmed or replaced. Similarly, the radio link may be swapped out as required for a given application, depending on wireless range requirements and the need for bi-directional communications.

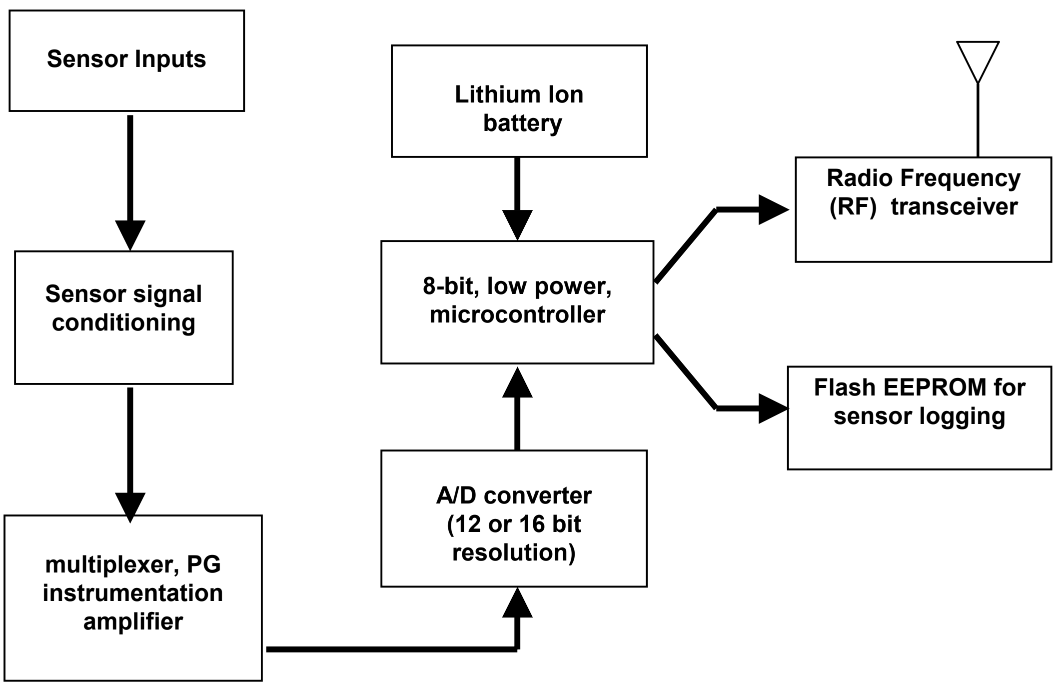

Figure 1. Functional block diagram of wireless sensing node with data logging and bi-directional RF communications capabilities. The processor manages power to the sensors and data acquisition elements, as well as responds to commands from the base station.

In order to allow multiple nodes to communicate simultaneously, the RF transceiver modules were upgraded from narrowband, fixed frequency surface acoustic wave (SAW) resonant types to frequency agile transceivers, which can be placed on a range of distinct RF communications frequencies through software commands from the microcontroller. This technique, termed frequency division multiplexing (FDM), allows multiple nodes to communicate simultaneously without potential for RF interference between the nodes. For example, up to 26 nodes may transmit digital sensor data simultaneously in the ISM band (902-928 MHz, bandwidth 76.8 kbaud). Furthermore, the RF power levels used for transmission may also be programmed in software.

These new transceivers are commercially available through several sources, including the model CC1021 from ChipCon (Oslo, Norway) and model XE1203 from Xemics (Neuchatel, Switzerland). The high sensitivity of these transceivers (>110 dBm) allow for license free, narrowband, bi-directional RF communications over distances of ~150 meters.

The FDM technique has been applied to a family of sensor modules for wireless sensor data acquisition called Agile-Link ™ (MicroStrain, Inc. Williston, Vermont, USA). The Agile-Link ™ product family includes nodes designed for use with wireless strain gauges, accelerometers, temperature sensors, and millivolt level inputs. Figure 2 is a photo of a miniature, frequency agile strain gauge module as developed by the authors. Accompanying base stations are commercially available with serial (RS-232 & USB), Sony Clie ®, and analog output interfaces. Figure 3 is a photo of four wireless base stations which are directly interfaced to the USB port of an IBM notebook computer. The base stations each operate on a separate frequency band, and draw power from the USB port, providing a fully portable and expandable wireless base station.

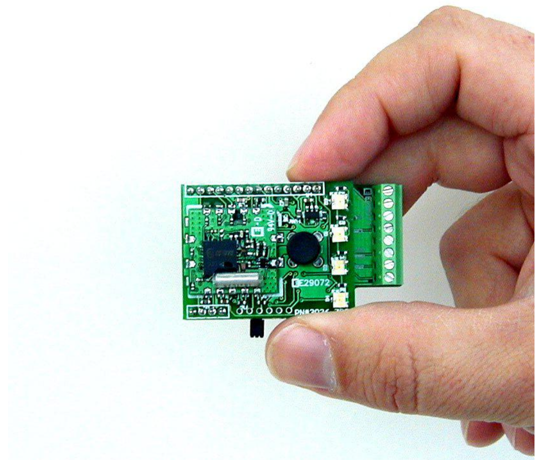

Figure 2. Agile-Link ™ wireless strain gauge node with integral rechargeable battery (MicroStrain, Inc)

Figure 3. The photo at left depicts data collection from four multi-channel sensor nodes simultaneously, by connecting, four distinct miniaturized Agile-Link ™ wireless USB base station transceivers to a 4-way USB hub. Each transceiver operates on a distinct RF carrier frequency.

Test & measurement applications often require the combination of wireless sensing systems to be used alongside hard-wired sensors, all connected to an existing analog data acquisition system. In order to easily support these applications, microprocessor enabled base stations which reconstruct the analog voltage waveforms on their outputs were developed. Figure 4 is a block diagram of the frequency agile system with analog output. The analog output base station includes a microprocessor, hardware low pass filter, and 12-bit digital to analog converter (DAC). The serial data stream is converted by the base station into high level analog output voltages, ranging from 0 to 5 volts full scale.

Digital RF communications possess several advantages over traditional analog methods; digital data is very "clean", or hard to interfere with. Another advantage of digital RF communications is that any errors caused by interference can be flagged by sending a checksum byte. The received checksum byte is compared to the calculated sum of the received bytes by the base station. If the calculated sum does not equal the received checksum, the processor within the base station can flag these data. MicroStrain provides a unique "checksum channel" on its Agile-Link ™ analog output base stations. The checksum channel is programmed to output a high analog voltage in the event that a checksum is detected; this voltage is easily interfaced to traditional analog data acquisition systems.

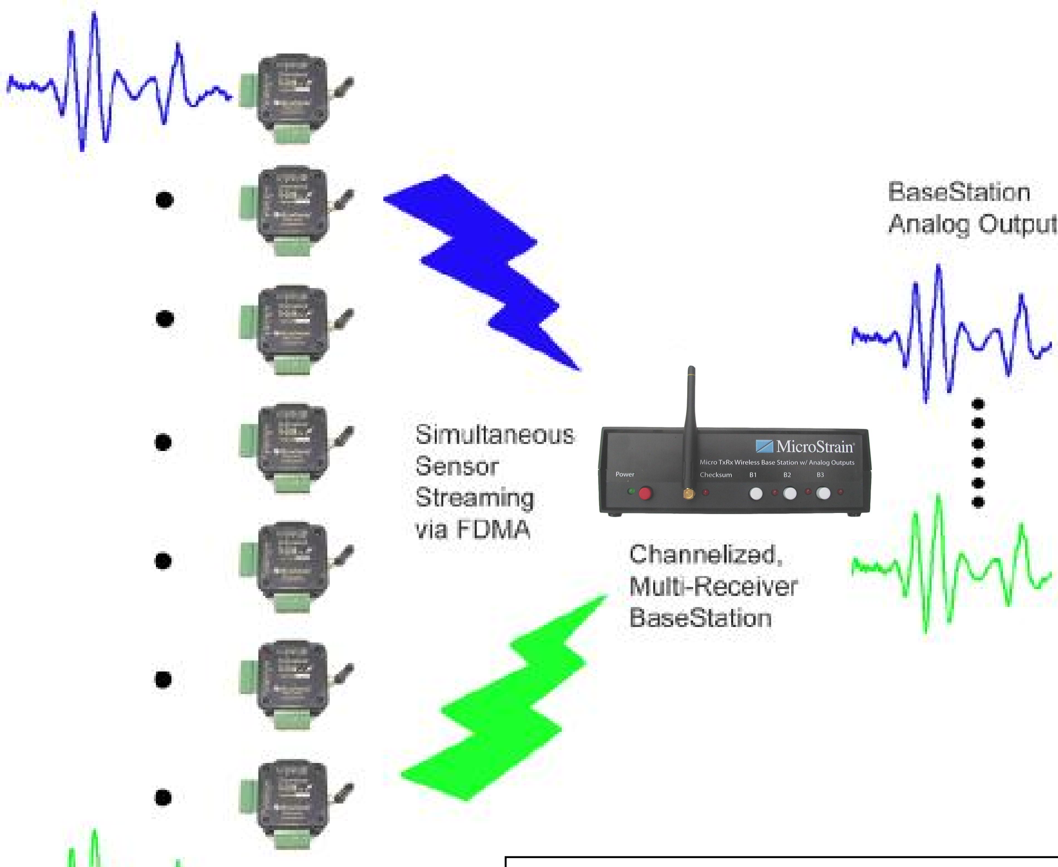

Figure 4. Analog output base station (Agile-Link ™, MicroStrain, Inc.) collects data from multichannel Agile-Link ™ sensor nodes and reconstructs their analog waveforms. The sensor modules can sense strain, acceleration, temperature, pressure, load, torque, and millivolt/volt level differential and single ended signals.

One concern was that the reconstruction of analog outputs would result in time delays due to the "chain" of analog to digital conversions (at the sensor node) followed by digital to analog conversions (at the base station). The anti-aliasing low pass filters at the sensing node and the low pass filter at the analog output base station were -3db at 500 Hz, with -40 db/decade roll off.

To measure the processing delays, we used a function generator (BK Precision model 4011A, 5 MHz) and digital oscilloscope (Tektronics model TDS 2024, 200 MHz). Triangle waves (at 18 Hz frequency) from the function generator were connected as an input to the wireless sensing node while this same waveform was simultaneously played into channel one of the oscilloscope. Triangle waves were used because their sharp peaks were easy to identify, which made the manual measurement of the phase delay easier to accomplish on the digital oscilloscope. Data from the wireless sensing node was sent (via RF) to the analog output base station, where it was reconstructed as an analog voltage, this output voltage was connected to channel two of the oscilloscope. The time delay between the two waveforms could then be directly measured. These tests were performed for one, four and eight active sensing channels per wireless sensor node. Figure 5 is a line drawing of the test setup used to determine the time delays associated with the MicroStrain, Inc. analog output base station.

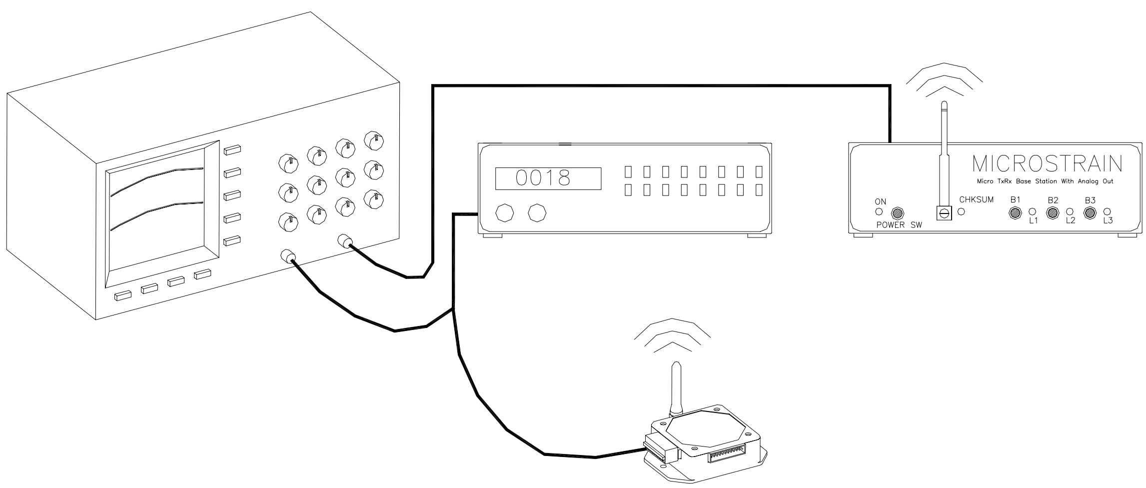

Figure 5. Test setup for determination of the time delay through the analog output base station. The function generator output (18 Hz) was connected to the oscilloscope's channel 1 input, and to the wireless sensor node's input. The wireless sensor node transmits data to the base station, which converts the data into an analog waveform. This reconstructed waveform is input to channel 2 of the oscilloscope.

In order to determine the temperature coefficients of the wireless strain sensing nodes, we utilized a half bridge of 1000 ohm (Vishay Micro-Measurements, Raliegh, North Carolina) mounted to an aluminum beam in bending, along with an Agile-Link ™ wireless strain gauge node (MicroStrain, Inc. Williston, Vermont) to a range of temperatures in a programmable environmental chamber (Thermotron). The beam was kept at room temperature, outside of the chamber, in order to allow us to determine the effects of temperature on the wireless sensing node only (independently of the variations in output that may occur in the aluminum beam and the strain gauges themselves). Offsets were measured at a range of temperatures, and shunt calibrations were performed manually on (external) connections to the strain gauge bridge, without disturbing the bridge mechanically.

4. RESULTS

The phase delays of the frequency agile, analog output base station were found to depend on the number of channels that were transmitted from the wireless sensing node. The delays were also found to be very repeatable. The delay (or lag) in the systems response from the analog output base stations was 1.5 milliseconds, 3.5 milliseconds, and 5.5 milliseconds for 1, 4 and 8 active channels, respectively. This yielded a nearly linear relationship ($y = 0.5676\ x + 1.0405$, $R^2 = 0.9932$, where y is the delay in milliseconds and x is the number of active channels). This equation allows the end user to apply a phase delay correction to multi-channel data in order to synchronize those data collected wirelessly with those data that may be hard wired to their data acquisition system.

Environmental and phase delay test results of multi-channel Agile-Link ™ wireless sensing nodes combined with conventional piezoresistive foil strain gauges (1000 ohm) are summarized below:

- Sample rates: 1700 samples/sec with one active channel
- Phase delay: 1.5, 3.5, & 5.5 milliseconds for 1, 4 and 8 active channels
- Temperature coefficient offset 0.007%/deg C (tested from +20 to +50 deg C)
- Temperature coefficient span 0.004%/deg C (tested from +20 to +50 deg C)
- Operating temperature: -20 to +85 deg C
- Programmable full scale range: 1000 to 5000 microstrain
- Resolution: +/-2.5 microstrain (w/ anti-aliasing filter bandwidth 0-500 Hz)

5. DISCUSSION

Frequency agile strain, acceleration and micro-displacement sensing nodes were used to protect the Liberty Bell during a recent move in October 2003. A 2000 pound “test bell” was placed on a wheeled conveyance and moved over the path that the actual Liberty Bell was planned to be moved along. The vibration data obtained from the wireless triaxial accelerometer node was used to make recommendations to the National Parks Service, such as smoothing the path for the conveyance, and pushing the conveyance slowly by hand. During the day of the actual move, three distinct wireless nodes were deployed on the Liberty Bell for a period of twelve hours, with continuous high speed data transmission during the entire twelve hour period. The three nodes were:

- Node 1: DVRT-LINK wireless displacement for visible crack (two channels, full scale range 0.5mm, resolution 0.25 microns, update rate 1200 samples/sec/ch)

- Node 2: G-LINK wireless accelerometers: (triaxial Analog Devices’ ADXL202’s, three channels, full scale +/-2G’s, resolution 1milliG, update rate 829 samples/sec/ch)

- Node 3: SG-LINK wireless strain gauges: at hairline crack tip (one channel, 1000 ohm bonded foil Vishay strain gauge, resolution ~3 microstrain, update rate 1700 samples/sec)

Figure 6 provides an image of the Liberty Bell while the move was underway. Separate RF carriers sent wireless node data to 3 USB ports these USB ports were supplied by two separate tablet PC’s (for data acquisition redundancy). No major sensor events were observed at any time during the actual transportation of the Liberty Bell by the wheeled conveyance. However, after the move was completed, the riggers were required to raise the Liberty Bell using a hand operated jack. During this maneuver, we observed micro-displacements of the visible crack with simultaneous strain activity at the tip of the hairline crack (Figure 7). We note that these readings did return to their original level, so no permanent deformations were observed. But the combination of visible crack motion with hairline crack strains was a concern and thus prompted the authors to ask the riggers to stop. After some discussion, the riggers continued at a much slower pace. During and after this slower raising activity, no significant strains or micromotions were observed, and the Liberty Bell was safely secured within its new home.

Figure 6. Photo of Liberty Bell while data were collected on two tablet PC's, for redundancy in observation and data collection. Three distinct, multichannel wireless sensing nodes (crack micro-motions, accelerations, and hairline crack strain) streamed data from the Liberty Bell to each tablet PC in real time.

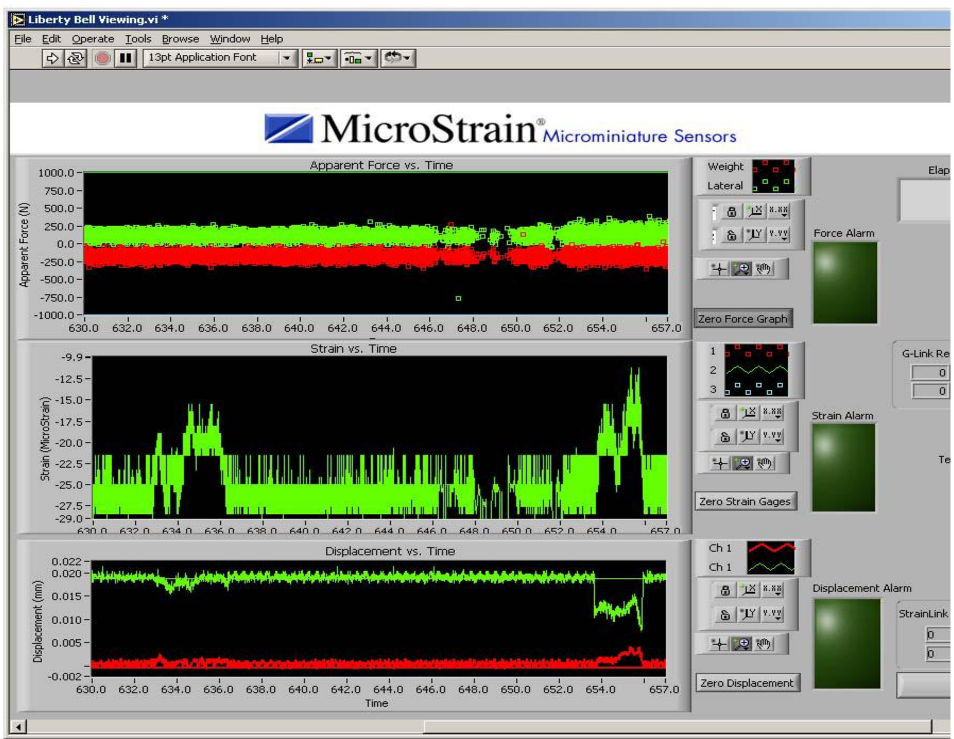

Figure 7. Screen shot of actual data collected from the Liberty Bell while lifting the Bell, after transportation had been completed. Micro-displacement activity of the visible crack measured ~10 microns during this activity. Strains at the tip of the hairline crack coincided with the crack micromotions. The readings returned to baseline levels.

6. CONCLUSIONS

- Wireless sensors provided an early warning detection system to safely transport the Liberty Bell
- FDMA wireless sensor nets were demonstrated
- FDMA analog output base stations have been developed that preserve digital checksum information
- These systems can be deployed for real-time wireless control with multiple nodes on the air simultaneously

The ability to collect data from multiple, multi-channel sensing nodes of strain, acceleration and temperature is enabling for many test and measurement applications, which has, in the past, relied heavily on laboratory simulations in order to validate new structural and machine designs. These new frequency agile wireless sensing systems are enabling "real-world" measurements, where designs are tested and validated in the actual operating environment.

7. ACKNOWLEDGEMENTS

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