

## Wireless Strain Sensing Networks

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### ABSTRACT

Our goal was to demonstrate a wireless communications system capable of simultaneous, high speed data communications, particularly adapted for use with conventional foil strain gauges. We have previously described data logging transceiver nodes capable of 2K samples/second/channel data rates. However, only one node may stream data at a time, since all nodes on the network share the communications channel.

To overcome these limitations, 2<sup>nd</sup> generation data logging transceivers were developed with software programmable radio frequency (RF) communications. Each node contains on-board memory (2 Mbytes), regulated sensor excitation, instrumentation amplifiers with programmable gains & offsets, multiplexer, 12 bit A/D converter, microcontroller, and frequency agile, bi-directional, frequency shift keyed (FSK) RF serial data link. The nodes are capable of continuous RF transmission from over 26 nodes, over frequency bands of 402-470 MHz & 804-940 MHz bands, at data rates of 76.8 kbaud.

An aluminum beam with half bridge, 1000 ohm bonded foil strain gauges was used to determine sensitivity (through shunt calibration) and to assess gain stability over temperature. With full scale range of 4000 microstrain, and anti-aliasing filter bandwidth of DC to 500 Hz, resolution was +/- 2.5 microstrain. Environmental chamber tests from +40 to 0 degrees C yielded gain coefficients of +.004%/deg C to +.06%/deg C and offset coefficients of -.007%/deg C to -.09%/deg C.

The system has been demonstrated for efficient quality control on Ford Motor Company's automotive production line. SHM with these wireless strain sensing networks on large civil structures are currently underway.

### INTRODUCTION

Sensors integrated into structures, machinery, & the environment, coupled with the efficient delivery of sensed information, could provide tremendous benefits to society. Potential benefits include: fewer catastrophic failures, conservation of natural resources, improved manufacturing productivity, improved emergency response, enhanced homeland security. However, barriers to the widespread use of sensors in structures and machines remain. Bundles of lead wires and fiber optic "tails" are subject to breakage and connector failures. Long wire bundles represent a significant installation and long term maintenance cost, limiting the number of sensors that may be deployed, and therefore reducing the overall quality of the data reported.

Wireless sensing networks can eliminate these costs, easing installation and eliminating connectors. The ideal wireless sensor is networked & scalable, consumes very little power, is smart & software programmable, capable of fast data acquisition, reliable & accurate over the long term, costs little to purchase & install, and requires no real maintenance.

Strain is an important measurement for structural integrity and machine condition monitoring. High magnitude, repetitive strains may lead to fatigue or yielding in the material. The strains can be used to estimate a structure's loads, moments, and stresses; or to validate a mathematical model. Frequency analysis can be performed on strain data for modal studies. Arrays of strain gauges combined with careful design can be used to create very accurate transducers of torque, load, pressure, and acceleration.

## 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 [1,2]. 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.

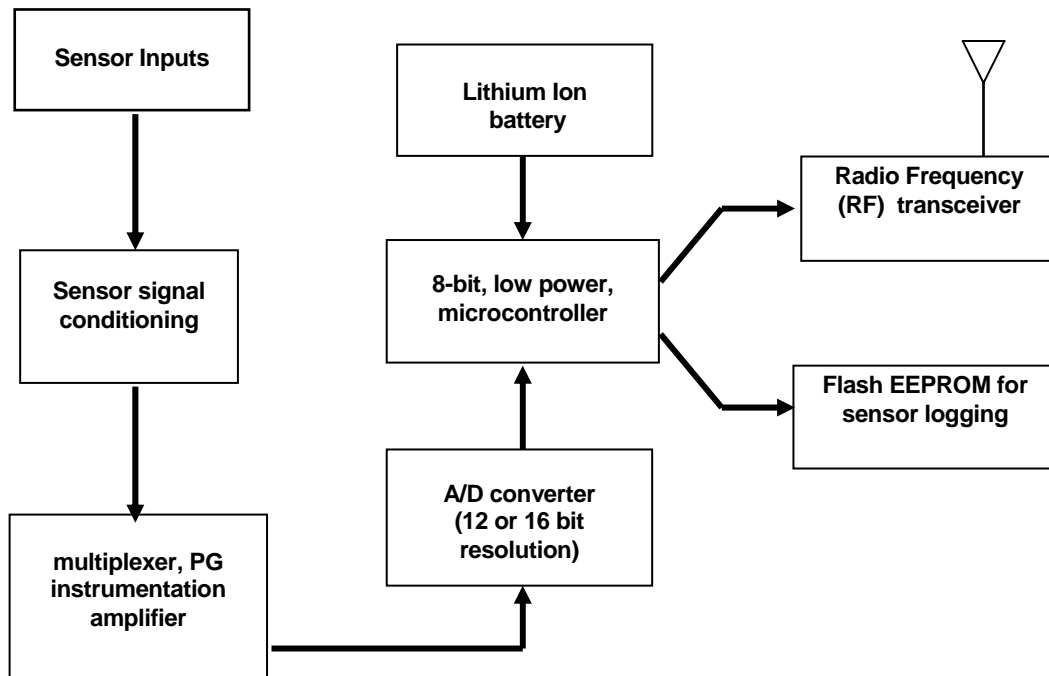


Figure 1. Wireless sensor node functional block diagram

For strain sensing applications, the ability to wirelessly program sensor offsets and gains has been an important feature of the signal conditioning, because strain gauges typically exhibit significant offset due to changes in resistance induced during installation. Furthermore, gain programmability is important because in many applications the full scale strain output is not known, and therefore the system gain must be set “on the fly”.

A key feature is the requirement for controlling the power consumed by the sensors and sensor signal conditioning. Multi-channel, wireless strain sensing power levels can be greatly reduced by the judicious use of microcontroller and radio sleep modes. To illustrate this point, we compare the power required for three distinct modes of operation:

Mode 1) wireless transmission of sensed data: 45 milliwatts.

Mode 2) processing/logging of sensed data: 5.0 milliwatts.

Mode 3) sleeping: 0.02 milliwatts.

In order to best take advantage of these extremely low sleep currents, the microcontroller’s built-in firmware was programmed to operate in a mode which automatically pulses power to the sensing portions of the electronics, while synchronously performing analog to digital conversions and RF communications. We have demonstrated this using a three channel, 1000 ohm/gauge, wireless strain gauge system. The system, if continuously powered, would draw, on average, ~25 milliamps from a three volt regulated power supply. By pulsing energy to the electronics & communications link at a rate of 10 samples/sec, the average current draw can be reduced by a factor of 100, down to ~ 250 microamps. This low power capability is enabling for long term battery operation, remote powering by external fields, and energy harvesting.

Another strategy to save power is to remotely command the wireless sensing nodes from a base station as required by the specific application. We have previously reported on addressable, wireless strain sensing nodes that implement the following modes (by base station broadcast address and/or node specific address command).

- Wake, listen for commands, log or transmit data as commanded, sleep
- Wake, log information when an event or threshold crossing is detected, sleep
- Wake, transmit data periodically, sleep



Figure 2. Compact, wireless strain sensing node with rechargeable lithium-ion battery

Addressable sensing nodes feature 2 Mbytes of on-board, non-volatile memory for data storage, 2000 samples/second/channel logging rates, 1700 samples/sec/channel over-the-air data rates, bi-direction RF link with remote offset and gain programmability, compact enclosure, integral rechargeable Li-Ion battery, and on-board temperature sensor. Figure 2 (previous page) provides a photograph of the packaged wireless strain sensing node.

These advances have allowed batteries to be deployed in a wide range of wireless sensing applications, including civil structural monitoring, automotive quality control, and medical research. For civil structural monitoring, automatic event driven triggering and the ability to place the sensing nodes in/out of sleep as required by civil structures engineers was critical to squeeze the most energy possible from remote batteries but still provide for high data acquisition rates as required by well controlled bridge testing protocols [3]. A diagrammatic representation of this system is provided in figure 3, below. The figure depicts a magnetic mount DVRT, however, conventional bonded foil strain gauges and weldable gauges have also been deployed.

A hierarchical structure controls the flow of data; the base station requests that a specific addressable node on the network send its data, and that specific node responds. However, many applications require that several nodes communicate data simultaneously in real time. Typically, these are measurement and control systems that include strain, acceleration, torque, and temperature sensors, which may be distributed over the structure under test. The wireless data obtained in real time may be used to protect valuable process equipment from torsional strain overloads, or to help research engineers to better visualize and interact with the system under test.



Figure 3. System for civil structures monitoring with multiple strain sensing elements

In order to best accomplish this, the wireless 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 RF communications frequencies through software commands from the microcontroller. This technique, termed frequency division multiplexing, allows multiple nodes to communicate simultaneously without 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  $\sim 150$  meters.

There is also often a requirement to combine the wireless strain measurement systems with other sensed data, which may be hard-wired to an existing data acquisition system. In order to easily accomplish this, we have upgraded our base stations to reconstruct the analog voltage waveforms. Figure 4 below is a block diagram of the frequency agile system with analog output. The base station includes a microprocessor, hardware low pass filter, and 12-bit digital to analog converter. The serial data stream is converted by the base station into high level analog output voltages, ranging from 0 to 5 volts full scale. In order to preserve the advantage of digital communications, 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 flags these data. This error flag is communicated to an analog data acquisition systems by providing an extra analog output channel. This “checksum channel” is programmed to output a high analog voltage in the event that a checksum is detected.

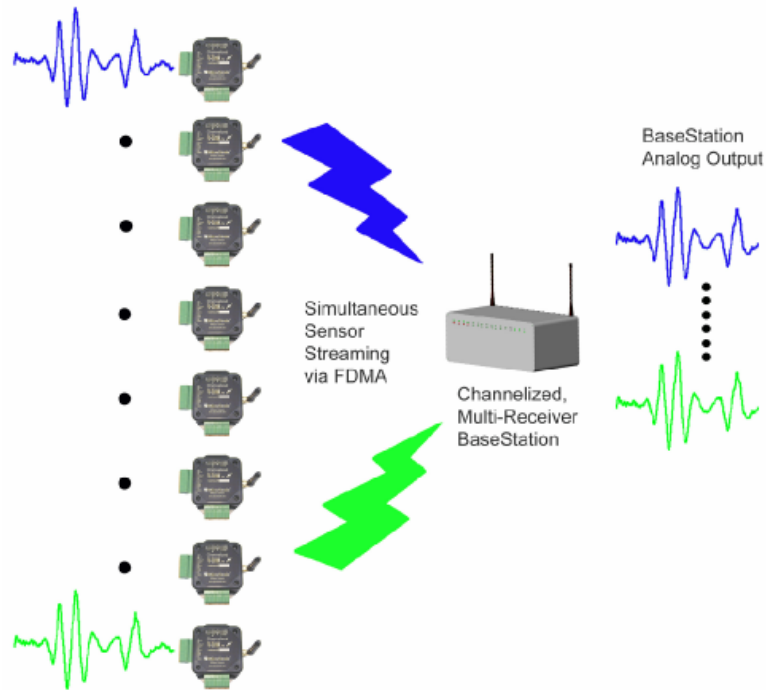


Figure 4. Frequency division multiplexed wireless sensing nodes with analog output base station

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 photograph of the test setup used to determine the time delays associated with the MicroStrain, Inc. analog output base station.

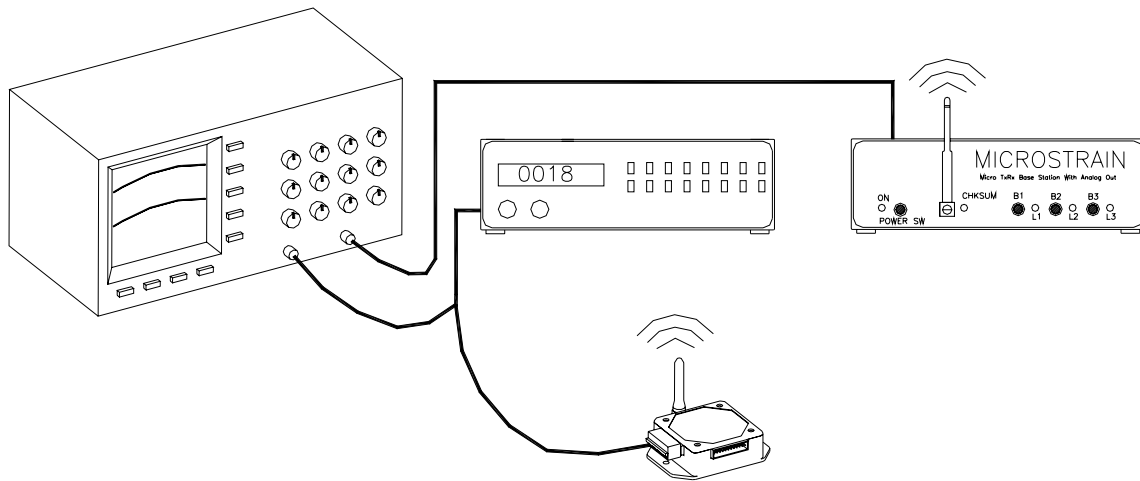


Figure 5. Test setup for determination of the time delay through the analog output base station. The function generator output (18 Hz) was connected to the oscilloscope's channel 1 input, and to the wireless sensor node's input. The wireless sensor node transmits data to the base station, which converts 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, Raleigh, North Carolina) mounted to an aluminum beam in bending, along with the SG-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.

## RESULTS

The resulting performance specifications for the wireless strain sensing node combined with conventional piezoresistive foil strain gauges (1000 ohm) are summarized below:

- 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)

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 ( $y = 0.5676x + 1.0405$ ,  $R^2 = 0.9932$ , 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.

## **DISCUSSION**

These wireless strain measurement systems can be deployed in a range of structural health monitoring applications. One important automotive application is in quality control of the gaps in body panels and doors [4]. Wireless strain sensors were deployed by the Ford Motor Company (East Lansing, Michigan) in collaboration with Metronom, USA (Detroit, Michigan) and MicroStrain Inc. (Williston Vermont) to facilitate measurement during the assembly process. The elimination of lead wires and the simultaneous acquisition of the gap data from multiple data logging transceiver nodes allows for rapid quality checks to be performed. The end user typically deploys as many as twelve wireless strain sensing node per door; these data are downloaded in approximately 5 or 10 seconds. Furthermore, because the wireless strain nodes feature a fast dynamic response, Ford Motor company engineers utilize these same wireless strain sensing nodes for continuous monitoring of automotive gaps during wind tunnel testing.

These programmable wireless strain sensing nodes are also being deployed on the Ben Franklin Bridge, which spans the Delaware River from Camden NJ to Philadelphia, PA. In this case, a network of wireless, weldable strain gauges with appropriately sealed IP67/NEMA4X enclosures log data periodically, according to an event driven requirement. Strain data from the nodes are archived by a wireless base station, which may be remotely accessed using cellular telephone communications. The ability to record data on the wireless node when a strain “event” is detected allows us to greatly reduce the amount of data that must be communicated over the airwaves, which preserves battery life and eases data analysis.

## **REFERENCES**

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