

# Smart Brick - A Low Cost, Modular Wireless Sensor For Civil Structure Monitoring

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## ABSTRACT

We report results on the design and implementation of a low cost wireless multi-sensor system to enable the creation of smart building materials such as smart bricks. We have demonstrated a proof-of-concept device that samples both digital and analog sensor data from a number of configurable sensors, processes the data, and wirelessly transmits it to a data collection receiver with a maximum range of 101m using a tiny helical antenna. Evaluation of the effects of common civil materials on system performance is also presented. Power consumption performance is evaluated and suggestions made for future work.

**Keywords:** Wireless distributed sensors, smart materials, civil monitoring

## INTRODUCTION

Recent advances in electronics have made it feasible to build low cost wireless sensing nodes in order to create networks for gathering data from distributed sources where wiring would be too difficult, dangerous, or expensive to implement. In an extreme case, the sensor nodes can be distributed in the millions over a wide area, while maintaining high spatial density so that node-to-node damage tolerant ad-hoc networking is enabled. In this scenario, extremely simple and inexpensive sensor nodes are required and could be useful for monitoring soil conditions for agriculture or toxic agent levels on the battlefield [1].

More mundane applications can be found for fewer, more complex sensor nodes that incorporate a flexible array of sensors as well as more powerful (and power hungry) transmission methods which reduce the sensor node density required for effective data collection. Small multimodal sensor nodes attached to patients or embedded in furniture could provide untethered monitoring of patients for efficient on-site or responsive home-based health care. Similarly, the health and status of civil structures such as skyscrapers, bridges, and even homes could be monitored using such sensors for scheduling routine maintenance or to assist in emergencies.

The promise of such applications has not gone unnoticed and a wide range of research and commercial development is being conducted to formulate efficient protocols specialized to wireless sensor network needs, design circuits to harvest power from the environment,

and to build smaller and more efficient sensor nodes [2-5].

Unlike traditional wireless applications such as familiar cellular phones, remote controls, garage door openers, etc, where the primary design parameter is quality of service, the primary concern of wireless sensor design is power consumption [1]. Various approaches are being put forward to reduce power needs for wireless sensing nodes in order to extend service lifetime and expand capabilities. For example, in a divergence from traditional protocols, sensor node "sleeping" is being implemented as an important aspect of power saving [2, 6]. In this way, sensor node uses on-board processing to predict future measurements and will turn itself off for a period of time based on this prediction. Other approaches include specialized ASIC (application specific integrated circuits) mixed signal integration to reduce size as well as current consumption [7].

In order to apply currently available wireless technologies to a specialized sensing application, we present a simple prototype flexible wireless sensor node to enable "smart" buildings. Independent of protocols and behavioral schemes that can be implemented within programmable logic on the sensor nodes, we investigate design challenges for incorporating wireless sensing into everyday building materials such as the common brick.

## SENSOR NODE DESIGN

The term "smart" has been recently applied to a wide variety of technologies. In the context of this work to develop smart building materials "smart" indicates that through in-situ monitoring of environmental parameters such as force, stress, temperature, tilt, moisture, etc. the simple building blocks that make up modern structures are enabled to provide long-term intelligence regarding their health, and the health of their surrounding environment. This is accomplished using a straightforward node architecture as shown in Figure 1, where the electrical power components are omitted for clarity. This architecture is in general similar to the basic structure of the wireless node as presented by numerous researchers [1, 6].

Based on this, the initial prototype uses a minimum of components to provide analog to digital conversion, sensor sampling, signal multiplexing, and data transmission. In order to maintain system simplicity, clock synchronization, time-stamping, and error correction functions are absent in the demonstrated

wireless sensor node. The “mother-node” software implements the necessary processing and data fusion. In comparison to wireless sensing technologies such as “Smart Dust” which use an embedded operating system (TinyOS [4, 5]) the demonstrated system relies on much simpler protocols and electronics to decrease power consumption and cost.

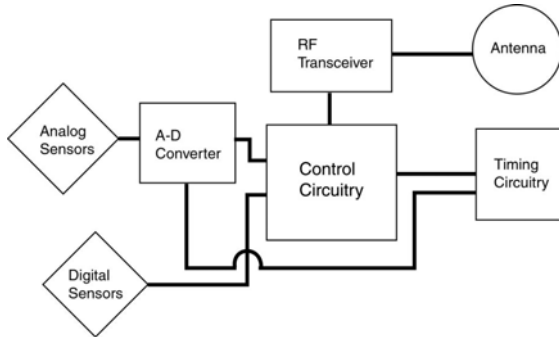
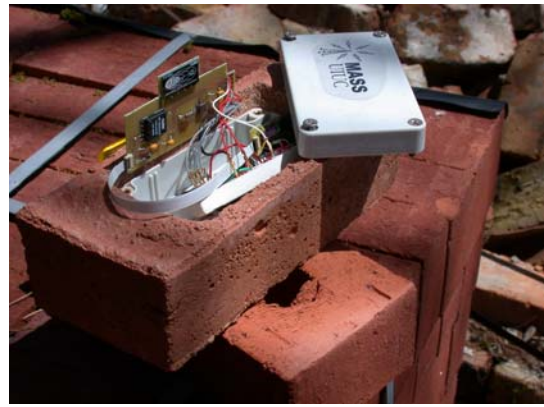


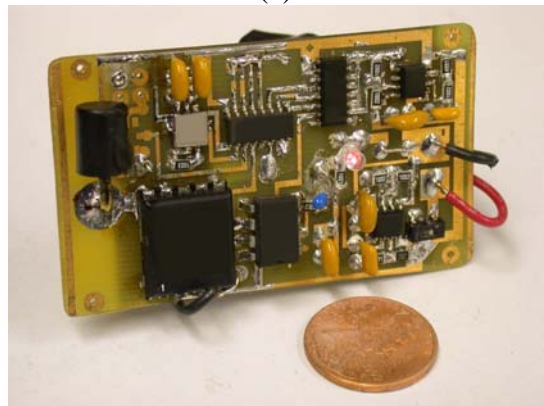
Figure 1: Block diagram of basic sensor node architecture.

The sensing package of the prototype wireless sensor node incorporates a pair of Analog Devices ADXL202AE 2g dual-axis accelerometers for three-dimensional vibration and tilt sensing as well as a standard 10k thermistor for temperature detection. However, the design is flexible and can include a variety of additional sensors depending on the application, such as sensors for detecting moisture, humidity, sound, chemicals, stress, force, and so forth. Cast into a brick as shown in Figure 2a or in a masonry block, the sensor node could be used in fire curtain walls found in stairwells to send information regarding the safety of building exits during a fire. The tilt and acceleration sensors would provide structural damage data while the temperature sensors would indicate areas of active burn or unsafe for exit due to compromised fire curtain. Such data collected from a distributed network of sensors in a large building or skyscraper could dramatically increase the safety of occupants and well as emergency crews.

The second prototype board shown in Figure 2b illustrates the design of the sensor node. The system utilizes the unlicensed 915MHz industrial, scientific, and medical (ISM) applications band, as well as a compact helical canister antenna. At this point, a number of compromises and simplification in design have been made to allow testing and software development. For example, the design utilizes an off the shelf stand-alone FM/FSK (Frequency Modulated/Frequency Shift Keyed) radio with integrated discrete components rather than a smaller, more efficient microprocessor controlled unit. In addition, to ease hand assembly, a number of large-scale discrete components are used rather than surface mount alternatives, and a power-hungry LED is included for indicating power.



(a)



(b)

Figure 2: (a) Photo of prototype wireless sensor system cast into a standard sized brick. (b) Close-up of improved board design with penny for scale.

The sensor nodes communicate with a “mother-node” in the form of a wireless receiver board coupled to a PC with an RS-232 cable. The “mother-node” uses a ¼ wave monopole antenna. The coupled PC runs a software data fusion program that decodes the incoming data stream into the various axes of acceleration and temperature. Figure 3 shows a screenshot of the real-time data collection software in action, tracking x and y-axis acceleration of the sensor node.

The sensor node combines the data from each channel (i.e. the accelerometer axes and temperature) and time multiplexes the data for transmission, with each “channel” receiving equal transmission time regardless of data content. This approach does not include any request-to-send handshaking, data headers, or error correction in an effort to maintain system simplicity and avoid node-side processing overhead and thus unnecessary power consumption. For the purpose of the presented tests these features were not required.

## SYSTEM TESTING

A variety of tests were conducted to validate and characterize the performance of the sensor node. Initial testing of the sensor node performance shows that analog

data can be reliably sampled, multiplexed with the other data channels and converted to a serial data stream, received by the base station, and reconstructed into an analog waveform via software. Figure 4 shows the result when a simulated sensor input of a 100Hz sine wave is input to the analog portion of the sensor node circuit and transmitted. With sampling frequency set at 650Hz, the waveform is regenerated after receiving with acceptable fidelity. For most building-scale applications, detection of inputs (vibration, temperature change, humidity change, stress, etc) with frequencies above 100Hz is not required and thus this test represents a worst-case scenario.

Power consumption at full RF transmission power is shown to be 22.5mW for the system pictured in Figure 2b, including the draw of the LED. Without the LED draw was 16.4mW. This is at least an order of magnitude above acceptable levels and as a result the battery lifetime at full power RF transmission and continuous data sampling is on the order of three weeks. Ongoing work is being conducted to improve these figures through adaptive transmission strength, exception and request based reporting, and utilizing “sleep” modes [6].

In order to evaluate the performance of wireless sensing system in an embedded “smart” building environment we conducted a detailed range test to determine the impact of common building materials on sensor node performance. Using a Garmin eTrex Vista GPS receiver, and taking advantage of the nearly ideal line-of-sight testing conditions offered by the flat cornfields of central Illinois we measured maximum reception range for the sensor node under a variety of conditions. The goals of the experiment were to measure the effect of the non-isotropic radiation pattern of the helical antenna design as well as observe the attenuation effects of various building materials.

Testing began by placing the sensor node on a camera tripod at 48” above the ground in an open field, with the sensor node circuit board ground plane parallel to the ground. A special range indicator circuit consisting of a receiver board and valid-data indicator LED was then moved around the field while position measurements were recorded using the handheld GPS. Data accuracy was not monitored, only valid data reception. GPS positional accuracy was reported as 15m according to the signals received by the eTrex handheld unit. The transmission range of the unenclosed sensor board was mapped in this manner, and is presented in Figure 5. The radiation pattern of the helical antenna is found to be non-uniform as expected, with an average range of 90m.

This process was repeated several times to observe the attenuation of a PVC plastic weather-tight enclosure, a wooden enclosure constructed of standard stud-grade

pine 2x4’s, and the concrete brick enclosure pictured in Figure 2a.

The results of this study are summarized in Figure 6, showing that the concrete brick attenuates the RF signal significantly, reducing the range to 28m. Figure 6 shows the average maximum data reception ranges for the 4 attenuation cases. The average attenuation for the plastic case, wood box, and concrete casting are 30%, 42%, and 68% respectively. However, the range for all 3 situations is still adequate for building scale application.

## CONCLUSIONS

As is the case for any wireless system, battery power is a major concern in the demonstrated design. Clearly the current prototype life of three weeks is not adequate for embedded long-term operation. As a result, current efforts are focused on reducing power consumption through adaptive transmission power, exception and request based reporting, and utilizing “sleep” modes. In addition, environmental sources such as thermal, solar, and inductive charging to supplement battery function are being investigated. Figure 7 shows a concept drawing of the implementation of these design goals. The investigation into “smart” building material packaging effects shows that incorporating such wireless sensing systems in skyscrapers, bridges, and even homes is feasible. The attenuation inherent in such structures also demonstrates the need for longer-range communication techniques in order to reduce the node density required to maintain network connectivity and thus reduce system cost.



Figure 3: Sample screenshot of real-time data collection software, with traces of X and Y-axis acceleration measurements. The horizontal axis is time and the vertical the duty cycle of the acceleration signals. A duty cycle of 50 indicates a neutral 0.0g alignment.

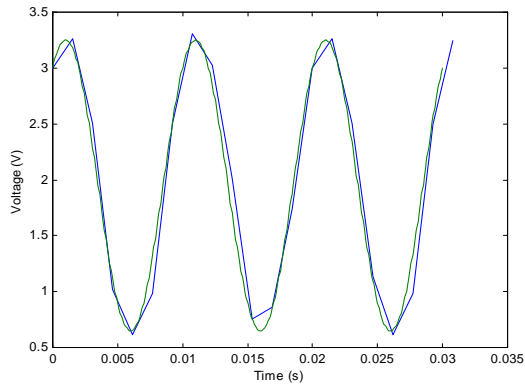


Figure 4: Analog data as received overlaid with input 100Hz waveform. Analog to digital conversion sampling rate is set to 650Hz.

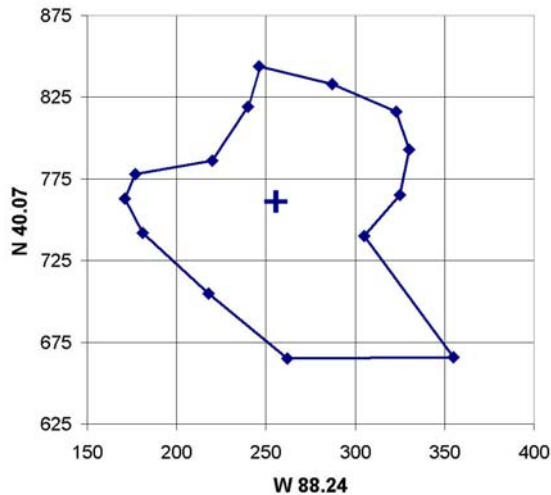


Figure 5: Test data for transmission range using helical antenna for baseline (unenclosed) sensor module. X and Y-axis units are the decimal minutes of GPS coordinates indicated in the axis labels.

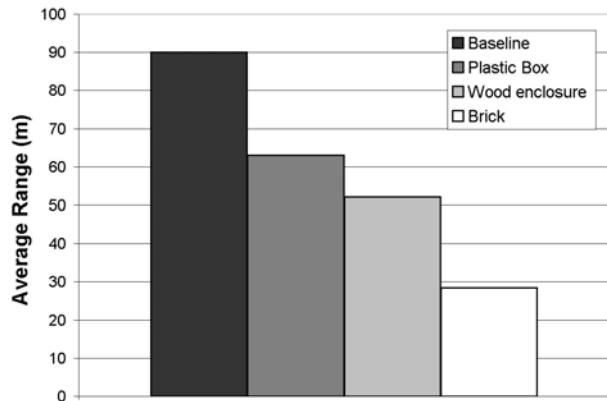


Figure 6: Test data for transmission range using helical antenna for baseline (unobstructed), plastic box, wood enclosure, and cement brick casting. Distances are averages of N,S,E, and W maximum ranges.

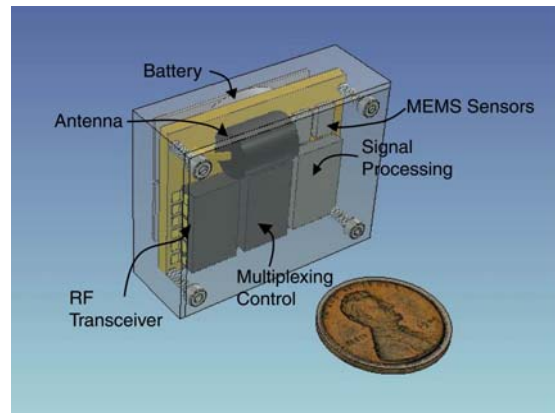


Figure 7: Concept drawing of next generation wireless sensor node design currently under way.

## References

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A survey on sensor networks," in **IEEE Communications Magazine**, vol. 40, 2002, pp. 102-114.
- [2] C. Rago, P. Willett and Y. Bar-Shalom, "Censoring sensors: a low-communication rate scheme for distributed detection," **IEEE Transactions on Aerospace and Electronic Systems**, vol. 32, 1996, pp. 554-568.
- [3] A. Chandrakasan, R. Amirtharajah, S. H. Cho, J. Goodman, G. Konduri, J. Kulik, W. Rabiner and A. Wang, "Design considerations for distributed microsensor systems," presented at IEEE Custom Integrated Circuits Conference, 1999.
- [4] B. Warneke, B. Atwood and K. S. J. Pister, "Smart dust mote forerunners," presented at IEEE International Conference on MEMS, 2001.
- [5] B. Warneke, M. Last, B. Liebowitz and K. S. J. Pister, "Smart Dust: communicating with a cubic-millimeter computer," in **Computer**, vol. 34, 2001, pp. 44-51.
- [6] J. F. Chamberland and V. V. Veeravalli, "The art of sleeping in wireless sensing systems," presented at IEEE Workshop on Statistical Signal Processing, 2003.
- [7] A. A. Abidi, "Low-power RF-ICs in wireless transceivers," presented at IEEE Symposium on Low Power Electronics, 1994.