Wireless Sensor Networks: From the Laboratory to the Field[*]

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ABSTRACT

This paper reviews the motivation for, and the design of, an environmental monitoring system based on a network of wirelessly-linked multi-parameter sensors. This approach enables access to more comprehensive data sets in a more timely fashion and with much less effort than is currently required. The design features the tight integration of existing, low-cost sensing, computation, and wireless communication hardware technologies with energy-aware processing and networking software, and can address immediate environmental monitoring needs. While our short-term focus is on environmental monitoring for microclimate field studies, the technology is also appropriate for a number of related applications, including ecosystem management, control of high-performance buildings, hazard/emergency warning systems, and security monitoring.

1. INTRODUCTION

Growing concern for environmental preservation is driving the requirement for improved understanding of microclimates. Researchers, managers, and the public need timely access to spatially rich datasets over potentially large coverage areas with minimal disturbance to wildlife. This suggests a distributed environmental monitoring system meeting several requirements:

1. Low cost - individual sensing units must be sufficiently inexpensive so that deployment at high spatial densities in large areas is not cost prohibitive.
2. Energy-aware design - constraints on cost and battery life require intelligent energy management to enable practical lifetimes in the field.
3. Flexible data rate - due to the slowly changing nature of most environmental parameters (e.g. temperature, humidity), the per sensor data rate is generally quite low. However, the system must be capable of handling high aggregate data rates from a large number of sensors.
4. Reliability and autonomy - the system must be robust to withstand long service intervals in the field with minimal supervision/maintenance.

Current microclimate monitoring technology is either prohibitively expensive for routine ecological research or the instrumentation is too bulky and/or invasive for *in situ* studies of wild organisms. Many researchers employ high-end sensors, approximately 200 cm^3 in volume, wired to centralized data loggers. These products have the required accuracy and reliability, but the installation cost and overall equipment expense precludes deployment in many cases, such as studies of microclimatic edge effects and work in forest canopies.

A currently-available alternative is small, inexpensive sensors integrated with dataloggers. While these units extend possibilities for field applications, coverage area and/or density is limited by invasiveness and/or the labor necessary to acquire data from large arrays of such devices.

There is little doubt that sensing of the physical environment will become ubiquitous in many aspects of 21st-century life. For example, one application of wireless sensor network technology is the monitoring of activity, comfort, energy consumption, air quality, and security in high-performance buildings. Rich and accurate sampling of multiple parameters can enable not only improved scientific understanding, but also improved energy efficiency, safety, and health care.

2. WIRELESS NETWORKING OF EMBEDDED SENSING DEVICES

Our design [1] synthesizes advances in environmental sensing (typified by current sensor/dataloggers) and a sophisticated wireless networking infrastructure that is carefully adapted to the environmental sensing regime. While the concept of integrating sensing/logging hardware with radio frequency (RF) communication capability is straightforward, we believe that integrated

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Military Surveillance	Environmental Monitoring
Performance-driven	Cost-driven
Mobile sensor nodes	Fixed sensor nodes
Dynamic physical topology	Static physical topology
Distributed detection/estimation	Spatio-temporal sampling
Event-driven/Multitasking	Scheduled single tasks
Real-time requirement	Delays acceptable/preferable

Table 1. Comparison of characteristics for two sensor network applications.

networking capability of the type we are developing will enable a new generation of ecosystem monitoring characterized by ground-breaking advances in both coverage area and density. We note that while networks of small sensors are receiving a great deal of research attention [2, 3], the predominant driving applications have been in the areas of military surveillance and chemical hazard warning. As shown in Table 1, the environmental monitoring application implies a unique set of characteristics; their implications have been largely unexplored.

One of our major priorities is keeping cost to a minimizing the total cost of manufacturing as well as deployment; we are targeting a per-sensor bill of materials in the range of $50. We believe that careful systems engineering will allow us to define an application niche in wireless communication that is not currently being served by voice- or data-oriented commercial wireless solutions.

3. OVERVIEW OF THE SYSTEM

System hardware design and component selection is critical to providing the necessary functionality while maintaining low system cost. We are constructing a codesigned hardware/software sensor node platform that can make use of future enhancements in sensor technology. Many aspects of the design utilize components already manufactured in high volume for other applications to take advantage of the consequent cost savings. Each sensing unit, which we call a WISARD (wireless sensing and relay device), employs a modular design that consists of three subsystems: a suite of sensors, a microcontroller, and an RF transmitter/receiver. The modularity extends to the ability to integrate different types and numbers of sensors; we are not pursuing fundamental developments in sensing technology, but rather the integration of advances as they become available.

Several previous experimental approaches have focused on scaling down full-blown systems such as laptops or 32-bit microprocessors designed for handheld PC's [4, 5]. On the other hand, a great deal of research is also directed toward fundamental sensing advances at micro- and nanoscales.

The goal of this project is to quickly bring a suite of complementary technologies to bear on a relevant problem. See Figure 1 for a photograph of the WISARD printed circuit board (PCB) containing the processor and analog sensing electronics (the board is 3.25 in. square). We employ a readily available 8-bit microcontroller (Microchip Technology's PIC16LF877) with integrated multi-channel analog-to-digital conversion and non-volatile data storage. Energy consumption is drastically reduced using the sleep mode during the many periods of inactivity in normal operation. The microcontroller contains in-circuit writable program storage to enable reconfiguration. Such reconfiguration could occur at different levels and could be autonomous and/or commanded remotely. The reconfiguration capability also allows convenient software changes, greatly facilitating the experimental components of the project.

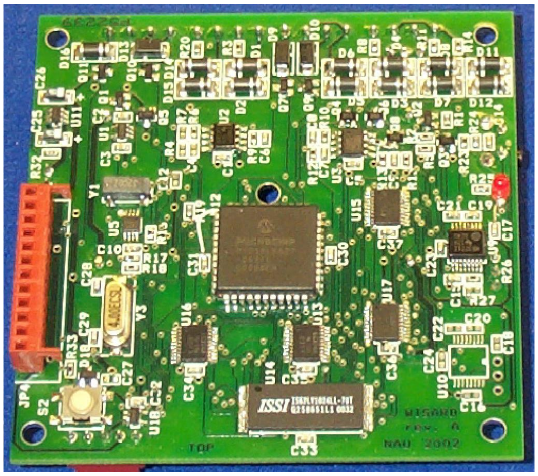

Figure 1. WISARD processor/analog module.

The microcontroller contains internal program memory for the device software and a small amount of SRAM for sensor data storage and radio communications processing. An analog-to-digital (A/D) converter also resides on-chip and is used for sensor measurement. The microcontroller has the ability to measure battery status and selectively power-down certain sections of the entire system for active power management.

Interface circuitry between the physical sensors and the microcontroller's A/D converter resides in the analog sensing section. This section contains a two channel thermocouple amplifier for direct interface with many types of thermocouple junctions as well as a two channel transconductance amplifier for interfacing with photodiode based light sensors. A general purpose analog input is included which may be used to measure the output of a humidity sensor, atmospheric pressure sensor, soil moisture sensor, etc.

Analog Inputs	**# of Channels**	**Sensor Type**
Temperature	2	thermocouple
Light	2	photodiode
General Purpose	1	any analog output device (i.e. - humidity, soil moisture, or pressure sensor)
Digital I/O	**# of Channels**	**Function**
Open Drain Output	1	general purpose control switch
Switched 3.3V Power	1	general purpose switched power source
1-Wire Bus	1	accommodates network of 1-Wire devices (counters, A/D converters, temp. sensors)

Table 2. WISARD input/output capabilities.

The digital peripherals section contains an assortment of additional system support functions. A real-time clock is included for timekeeping and periodic system wakeup (part of the active power management scheme). Two general purpose programmable digital outputs are provided for on/off control of external sensing equipment. An LED and pushbutton provide a simple interface for status indication and basic command input. One RS-232 serial port is also included for hard-wired communication with other equipment. Finally, a bi-directional synchronous serial port (over a single signal wire) has been implemented for use with devices (e.g., counters and A/D converters) that can communicate and derive their power supply from a single signal wire and a ground wire. These devices may be used to expand the sensing capabilities of the system to measure wind velocity and direction, rain rate, and countless other analog sensors.

The radio section utilizes a single-chip RF transceiver operating in the 902-928 MHz ISM band. As with the microcontrollers, these IC's are also produced in high volume for many other applications. The ISM band allows us to operate the system without a license but imposes strict transmit power constraints necessitating the use of the multi-hop network scheme.

Because unit-to-unit communication range is limited by both energy constraints and FCC regulations we utilize a multi-hop communication scheme in order to maximize overall system coverage area. Optimum routing in the multi-hop network will be key to system efficiency as the radio section is the largest power consumer within each sensor node. For high-density applications the network organization must be automatic and transparent to the user.

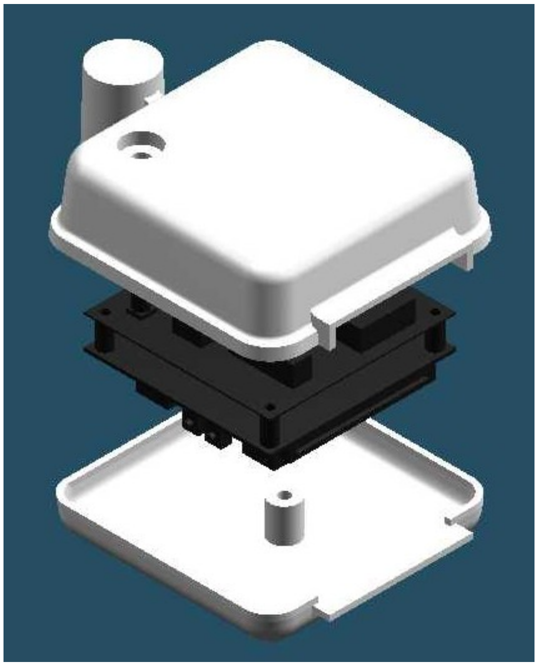

Figure 2. WISARD packaging.

The overall WISARD package design is shown in Figure 2. The electronics are assembled on a two-PCB stack (the lower PCB contains the microcontroller and analog sensor interface while the upper PCB contains the radio) that is contained in a two-piece molded plastic enclosure along with batteries. Sensor wires are connected to the device using screw terminals on the lower PCB and are routed out of the enclosure through a slot in the case seam. The slot contains a foam rubber gasket which compresses around the wires as the two case halves are assembled providing a weatherproof seal. The enclosure also features single-screw assembly for ease of sensor reconfiguration and battery changes, an external antenna mount, and a boss for mounting on a pole.

4. RESEARCH CONTEXT

Wireless networking topics continue to receive considerable research attention as the world becomes increasingly information oriented. A number of current challenges may be attacked using this same environmental monitoring platform as a research tool. The system's versatility and expandability in both hardware and software lends itself to experimentation that supports research in (i) distributed source coding of spatio-temporally correlated vector processes, (ii) multi-hop protocols with inter-layer interaction, and (iii) coded macrodiversity in energy-limited multi-hop networks. We are also planning to develop a simulation tool that will allow exploration of the communication and networking design space and its impact on per-node energy consumption.

5. CONCLUSION

Improved data acquisition is essential to progress in environmental and ecosystem sciences. Wireless technology provides the networking infrastructure critical for the non-invasive, near real-time acquisition of rich spatio-temporal datasets. The pragmatic approach outlined here addresses an immediate need in environmental and ecosystem monitoring while simultaneously providing a useful testbed for wireless sensor network research. It also serves as a baseline approach to the development of low-cost wireless sensor networks for myriad other applications.

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