WIRELESS SENSOR NETWORKS FOR DENSE SPATIO-TEMPORAL MONITORING OF THE ENVIRONMENT: A CASE FOR INTEGRATED CIRCUIT, SYSTEM, AND NETWORK DESIGN

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ABSTRACT

Research in environmental and ecosystems science is growing dramatically in importance as society becomes increasingly concerned about the environment and our impact on it. Researchers and resource managers must monitor a number of environmental variables in order to understand a wide range of phenomena, such as the impact of forest restoration or how fauna respond to microclimate gradients. Currently, these researchers use very basic stand-alone data logging equipment that requires a great deal of labor and does not easily lend itself to dense spatial sampling or near real-time data acquisition.

In this paper we present a design for a proof-of-concept microclimate monitoring system based on a network of wirelessly-linked multi-parameter sensors. This approach will enable access to a more comprehensive data set in a more timely fashion and with much less effort than is currently required. The design, therefore, addresses an immediate need in the unique application of microclimate monitoring while simultaneously serving as a testbed for basic research in wireless sensor networks.

1. INTRODUCTION

In the last decade, the predominant application driving wireless communication research has been mobile cellular telephony. Recently, more attention has been paid to the implications of ad-hoc, rather than infrastructured, networks. At present, interest is growing in applications that feature large collections of networked intelligent devices. For example, one can imagine indoor environmental control systems wherein networked sensor/actuator units distributed throughout the air handling system collaboratively minimize energy consumption while adapting to the distribution of occupants. There are also a number of compelling problems in which energy consumption of the nodes is highly constrained, including surveillance/tracking, hazard warning, and environmental sensing. One example environmental sensing application is high-density data collection in support of microclimate research. In this paper we motivate this problem, outline our design approach to a wireless sensor network for microclimate monitoring, and briefly discuss fundamental research issues. The overarching theme is that this application has unusual attributes (e.g., low data rates) that, taken together, imply that a holistic design approach is necessary to maximize energy efficiency.

This paper is organized as follows: environmental monitoring applications and their distinct needs are outlined in Section 2. Section 3 provides an overview of our design and its operation. Sections 4 address some of the key hardware and software issues of the design. Finally, Section 5 discusses how this system may also serve to facilitate continued research in wireless networking.

2. THE ENVIRONMENTAL MONITORING CHALLENGE

The continually growing concern for environmental preservation fuels a great need to have a better understanding of microclimates - the suite of climatic conditions measured in localized areas. At the scale of a few to a few hundred m^2, microclimates are influenced by regional climate patterns, topography, and vegetation cover. From an ecological perspective, the integrated influences of these factors define, to a large extent, the environmental variability that most organisms experience [1, 2]. Microclimatic conditions may have profound impacts on the survival and reproduction of plants and animals (e.g., [3, 4, 5]), and on key ecosystem processes such as photosynthesis, soil respiration, decomposition, and nutrient cycling (e.g., [6, 7]). Ultimately, it is the mosaic of microclimates that sets the stage for the diversity of organisms and ecological interactions present on

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the landscape. This points to the importance of developing a quantitative understanding of human impacts to microclimate, acting through changes in vegetation structure and disturbance regimes. Three environmental applications where wireless can enable a new level of performance are summarized below. This improvement is critical to the development of accurate models of ecosystem processes.

- Monitoring microclimate at avian nest sites in managed habitats.
- Measuring landscape-scale microclimatic variation to determine its effects on animal behavior.
- Understanding variation in microclimatic conditions in woodlands and forest canopies.

Given the vital role of microclimate, the high-density measurement over landscape-scale regions of key time series including air temperature, soil temperature and water content, insolation, relative humidity, and wind velocity are essential. However, overall cost constraints associated with existing technology have prevented monitoring at the spatial densities needed to improve models and, ultimately, understanding of ecosystem processes.

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 studies 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 (extensive cabling required) and overall equipment expense precludes deployment in many cases, including studies of microclimatic edge effects, work in forest canopies and other landscape-scale drivers of microclimatic variability.

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 the data from a large array of such devices. The units must be interrogated individually approximately every few days using a laptop computer or similar device. Obviously, this is not a viable solution for long term monitoring in remote areas nor does it allow any sort of automated reporting back to the researcher.

For these reasons researchers and managers 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 in large numbers is not cost prohibitive.

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.

2. Low energy consumption - energy is a precious commodity due to the remote nature of the system. System efficiency must be high in order to realize practical service life in the field.
3. Flexible data rate - due to the slow 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. Centralized data access - the labor necessary to extract data from individual non-networked units quickly makes large sensor arrays highly impractical. Data from all sensing units must be automatically delivered to a central repository.
5. Reliability and autonomy - the system must be robust to withstand long service intervals in the field with minimal supervision/maintenance.

3. WIRELESS ENVIRONMENTAL MONITORING

Our design 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 it is the integrated networking capability that we propose to develop on such a platform that will enable a new generation of ecosystem monitoring characterized by groundbreaking advances in both coverage area and density. We note that while networks of small sensors are receiving a great deal of research attention [8, 9], 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.

Because unit-to-unit communication range is limited by both power supply constraints and FCC regulations we uti-

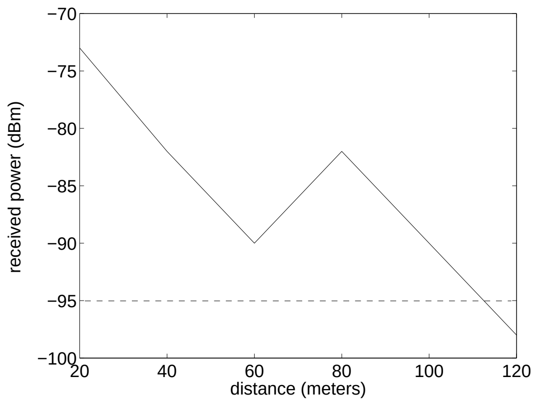

Figure 1. Received signal strength measurements

lize a multi-hop communication scheme in order to maximize overall system coverage area. In order to better understand the performance of low-power transceivers in typical environmental sensing field conditions we took propagation measurements using some commercially available equipment in the local Ponderosa pine forests. The transmitter and receiver used for this exercise operate in the unlicensed 902-928 MHz ISM band and have performance specifications very similar to the radio section of our sensor units. The devices were placed in a fairly level area which was populated primarily with Ponderosa pine trees. The transmit and receive antennas were both at a height of 1 meter above ground. Figure 1 shows a sample of the observed signal strength plotted against distance with the dashed line at -95 dBm representing the typical receiver sensitivity. It is obvious that, with the restricted transmit power, our unit-to-unit range is limited to approximately 100 meters in these conditions. During this work we also found that antenna heights less than 1 meter severely degraded system range. With the antennas at one-third of a meter above ground the units could reliably communicate over a distance of only 50 meters. Since most deployment situations would span distances greatly exceeding the direct point-to-point communication range (a linear array of sensors 1 km long would not be uncommon) we can capitalize on the high spatial density of units (relatively short unit-to-unit distances) by relaying messages from one unit to the next until they reach the base.

A typical deployment of the wireless sensor network would be composed of multiple sensor units, each containing an RF transceiver, and a base/central control unit as depicted in Figure 2. The sensor units may be placed in virtually any spatial arrangement provided the distance from any one unit to the next is not greater than the maximum unit-to-unit communication range. Once all units have been installed the system will begin a learning process to determine the optimum communication paths between sensors

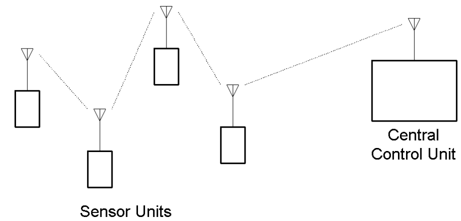

Figure 2. Wireless monitoring system

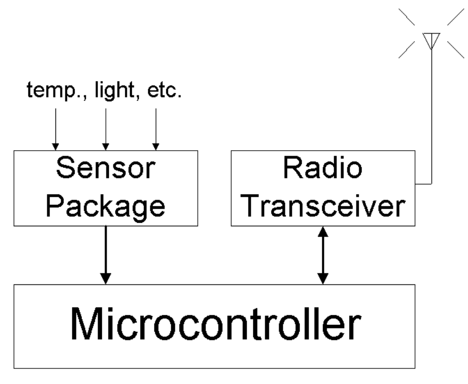

Figure 3. Sensor functional components

and generate a network routing plan. During system operation sensor units will periodically measure environmental parameters and store the data in their respective non-volatile memories. Then, on a predetermined schedule (typically with a frequency less than the sample rate), each unit transmits its data back to the base unit for mass storage or forwarding directly to a research facility. The base unit functions as the central control point and data repository for the system. Once the system has been installed in the field all control and data access is through one central point thereby simplifying the field technician's job of collecting data or giving commands/updates to the individual sensor units. Furthermore, the base unit may be linked directly to the research facility via long distance wireless data services such as satellite or cellular, relieving a technician of the burden of making periodic trips to interrogate the system while providing real-time access to the data.

4. SYSTEM ARCHITECTURE

4.1. Hardware Design

System hardware design and component selection is critical to providing the necessary functionality while maintaining low system cost crucial to making this solution practical. Many aspects of the design utilize components already manufactured in high volume for other applications to take advantage of the consequent cost savings. The units employ a modular design that consists of three subsystems: a suite of sensors, a microcontroller, and an RF transmitter/receiver (Figure 3). The modularity extends to the ability to integrate different types and numbers of sensors; we will not pursue sensing technology development, but rather integrate 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 [10, 11]. Here, we employ a readily available 8-bit microcontroller with integrated multi-channel analog-to-digital conversion and non-volatile data storage. Power consumption is drastically reduced using the processor's sleep mode during the many periods of inactivity in normal operation. The microcontroller's duties include system timekeeping, sampling appropriate sensors on a pre-determined schedule, data compression for storage and transmission, and channel encoding/decoding and error handling of the RF link. Finally, 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.

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 previously discussed. All major functions including the PLL, LNA, mixer, demodulator, and transmit modulator/PA are integrated on the chip to create an FSK data radio with only a handful of external components for filtering and tuning. The selected transceiver also permits adaptive transmit power (e.g., [12, 13, 14] and the references therein), data rate, and carrier frequency. The last parameter will be critical when frequency selectivity occurs, such as in canyons or environments with buildings or other structures. We will use this three-dimensional adaptivity to advantage at the network level [15] for routing table synthesis.

Ultimately, each unit must be able to sense key environmental parameters which requires precise, reliable physical sensors and their associated excitation and signal conditioning. It is our intention to provide a platform which can make use of future enhancements in sensor technology. Therefore, our sensor interface includes the ability to handle typical analog sensor outputs such as current, voltage, and resistance as well as digital pulse outputs (count, frequency, etc.). Units will also provide a number of configurable voltage and current excitation outputs to accommodate different sensor requirements.

4.2. Network Organization

Optimum routing in the multi-hop network will be key to system efficiency as the radio section is the largest power consumer within each unit. Since we are targeting large density applications the network organization must be automatic and transparent to the user. In order for the system to be of practical use the field technician should only need to place the sensing units in the desired locations without having to program each unit with location or identification data; once the system is powered it should organize itself. To accomplish this task we use a shortest radio path algorithm, similar to the Bellman-Ford algorithm, with a receive signal strength metric. Each radio receiver contains a receive signal strength indicator (RSSI) which will be used to identify other units nearest itself. Once the system has been installed the base unit initiates the process by sending out a message instructing all sensors within receiving range to identify themselves. As each sensor reports back the base station keeps record of their identification and their respective signal strengths. This process is repeated by the nearest sensor unit (the sensor who reports back with the highest signal strength) until all sensors have been located and assigned their position in the network based on relative signal strength.

4.3. Energy Management Strategy

Active power management schemes are critical to providing practical service lives to each sensor unit while utilizing low cost power sources. Optimization in isolated areas without regard for total system consequences could result in an overall penalty. Software and hardware must be jointly considered to maximize opportunity for savings. We employ aggressive power-down strategies on a number of fronts:

Radio receiver - Data transfer throughout the system will take place on a predetermined schedule therefore, each unit's receiver need not be continuously powered and listening. The schedule is known to each unit which will only turn on the radio when appropriate. In many cases transfers may take place only once an hour thereby maintaining a low receive duty cycle.

Sensor suite - Obviously, the sensors, analog conditioning circuitry, and analog to digital converter need only be powered during a measurement cycle. Fortunately, the slow changing nature of the variables being observed allow relatively infrequent measurements (approximately every 5 minutes in many cases).

Processor and memory - Relatively infrequent communication and sensing events leave little else for the processor to do except timekeeping. The microcontroller selected for this project contains a counter which may be incremented while the processor is in sleep mode (power consumption in sleep is 50 μW). Through the interrupt associated with this counter the processor is awakened periodically to see if there are any scheduled tasks.

4.4. Software Reconfiguration

In order to ensure system adaptability and flexibility, especially for some of the targeted research issues (Section 5), we have selected a microcontroller which contains writable program storage that may be modified by the microcontroller itself. This feature has a number of key benefits for both system development and operation.

Software updates - During development and throughout system lifetime periodic changes to the sensor and base unit software will be necessary to correct errors and add or modify functionality. Even if the system has already been deployed these modifications may be made simply by uploading new software to the base unit and allowing it to broadcast the software to all sensor units.

Static parameter storage - Certain system parameters which require relatively infrequent change may be stored in code space thereby freeing up other on-board non-volatile memory for other uses.

Continued research - Ease of reconfigurability makes this platform ideal for continued research in wireless networking applications. The hardware interface to the environmental sensors is very flexible and may include a variety of other tasks such as unit orientation or antenna positioning actuators.

5. FUTURE RESEARCH OPPORTUNITIES

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:

Distributed source coding of spatio-temporally correlated vector processes - Consider the sampling of an environmental variable (e.g., temperature) in a microclimate, for example at a temporal interval of 5 minutes and a spatial interval of 10 m. This data set will be highly correlated over space and time so that distributed source coding can dramatically reduce the energy required to acquire the data. As indicated in Table 1, the non real-time characteristic of this application implies that delay should be exploited to allow efficient coding. It can also mitigate the problem wherein nodes nearest the local destination (a central controller, perhaps with a satcom link) must relay the the greatest amount of traffic, thus leading to an imbalance in energy consumption [16]. Here, the source coding algorithm (normally a presentation-layer concern) will have a direct impact on what is usually considered a problem of low-power circuit design or a physical-layer network issue. Source coding approaches must consider combined transmit and receive energy per bit, fractional rate loss due to packet overhead, and delay. Coding of multiple parameters (e.g., temperature and insolation) leads to the case of coding of vector processes with correlated components. Finally, adaptivity to local and global spatio-temporal gradients may provide further benefits.

Multi-hop protocols with inter-layer interaction - Interaction between lower layers may prove very beneficial to network routing, source coding, or other system issues. It was projected in [17, 18] that classic layered protocols might be extended—or even abandoned—as networking finds new applications. Wireless sensing appears to be a scenario where new metrics such as energy use will motivate such a reexamination.

Coded macrodiversity in energy-limited multi-hop nets - If simple antennas are used, each node's transmissions may be detectable at multiple neighboring nodes, admitting macrodiversity at each hop. The key question here is whether coded macrodiversity can provide improved end-to-end performance in terms of reliability and energy efficiency. This will depend on energy consumption for both RF and baseband processing, including decoding [19]. Our goal is to find quantitative models that can be used to identify scenarios where macrodiversity provides an overall gain.

6. CONCLUSION

Future modeling work in environmental and ecosystem science depends on improved field data acquisition. Wireless technology provides the networking infrastructure critical for the acquisition of rich datasets. Realizing an efficient and practical system demands consideration of all subsystems and their inter-operation during the design process. The approach outlined in this paper addresses an immediate need in environmental and ecosystem monitoring and provides a useful testbed for wireless sensor network research.

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