WiSARDNET: A SYSTEM SOLUTION FOR HIGH PERFORMANCE *IN SITU* ENVIRONMENTAL MONITORING

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ABSTRACT

WiSARDNet (Wireless Sensing and Relay Device Network) is an ad hoc wireless sensor network optimized for dense in situ spatio-temporal monitoring of environmental and ecosystems processes. WiSARDNet is a complete distributed sensing system that includes (i) an array of standard multi-channel passive and active probe interfaces (e.g., multiple channels of temperature, light, and soil moisture) in each sensor, (ii) extensibility to other probes via multiple interfaces, and (iii) a PC-based human/network interface for network monitoring and control. These features, combined with an energy-efficient hardware/software architecture and network protocol stack, as well as careful energy management in a weatherproof package, allow high-performance data collection for large-scale scientific field studies.

1. INTRODUCTION

In situ monitoring of environmental and ecosystems processes at much higher densities and over larger areas is likely to vastly improve the modeling of these processes and lead to the discovery of new classes of emergent phenomena. Wireless communication and networking can provide the technological infrastructure that will enable the needed improvement, while minimizing invasiveness and cost.

Wireless environmental sensing has tremendous benefits, and environmental scientists are becoming increasingly aware of its potential [3,12]. At the same time, fundamental research directed at understanding the communication- and network-theoretic properties of generic energy-aware wireless sensor networks is underway worldwide [5,17,18]. Small-scale proof-of-concept networks that target the environmental sensing application are under development [1,4]. These projects indicate that the promise of wireless sensor networks for environmental monitoring--arrays of hundreds or thousands of small, inexpensive sensors that gather information and cooperate to relay that information to the ultimate destination---will soon be realized.

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The technical goals of this work are to develop robust prototype large-scale wireless environmental sensor network technology that is applicable to a wide range of habitats and experimental regimes, and deploy this technology in three diverse, large-scale ecological field studies that will generate rich datasets and contribute to progress in several areas. Other goals (not described here due to space limitations) are to build awareness of the benefits of this technology to society, and improve collaboration between engineering and the biological and ecological sciences.

This paper is organized according to our design hierarchy. In the next section, we describe the requirements for our system. Section 3 discusses the architecture, which integrates wireless networking and communication with sensing. Sections 4 and 5 describe the co-designed hardware and software that support the architecture. Applications are discussed in Section 6. Some of the challenges we have faced are described in Section 7, and conclusions follow in Section 8.

2. SYSTEM REQUIREMENTS

To meet researchers' and managers' needs for timely access to spatially rich datasets over potentially large coverage areas with minimal disturbance we identified the following requirements for a wireless sensor network [12]: *sensing accuracy* - sufficient for research-quality scientific data acquisition; *probe flexibility* - support of a broad spectrum of physical probe technologies; *scalability* – to support network deployments with diversity in network size and spatial density; *flexible data rate* - due to data aggregation, demanded rates will increase with proximity to gateways; *reliability and autonomy* - the system must be robust to withstand long service intervals in the field with minimal maintenance; and *low cost*.

Efficient wireless sensor networks require an integrated circuit, system, and network design [12]. Based on our first-generation proof-of-concept WiSARDNet (Wireless Sensing and Relay Device Network), we identified two primary goals for the prototype system:

Increased network capacity and redundancy – For the environmental sensing application, wireless sensor networks are characterized by dominant information flows: since all information must ultimately arrive a relatively smaller number of special *gateway* nodes, nodes closer to the gateways must handle more traffic, thus causing depletion of their energy at higher rates [11,19]. While our proof-of-concept design employed only one gateway for simplicity, the prototype network can use multiple gateways to enhance response time, lengthen network lifetime, and increase reliability.

Support of high-resolution sensing – The proof-of-concept nodes employed the microcontroller's on-chip analog-to-digital converter with 10-bit resolution. While sufficient for demonstration of the technology (e.g., measuring temperature and insolation), this resolution is not sufficient for all measurements. Thus our prototype WiSARDs use a 12-bit converter, increasing resolution by a factor of four. This resolution supports the broad range of measurements needed in this study, including soil moisture, relative humidity, heat flux, and leaf wetness in addition to temperature and light intensity.

3. WiSARDNET ARCHITECTURE

The WiSARDNet protocol stack integrates the physical, data link, and network layers in the service of energy efficiency and scalability; algorithms are distributed and rely only on local information. Our architecture is driven by the environmental sensing application, wherein most communication transactions can be scheduled because temporal sampling rates for environmental phenomena are very low. We note that these rates are not necessarily static: adapting sampling rates to hot or cold spots in time or space allow for improved data quality at a fixed average sampling rate.

In this context, we developed an integrated network protocol stack based on the proactive coordination, or scheduling, of communication transactions. This is in contrast to reactive, or contention-based, approaches (e.g., Bluetooth and 802.15.4/Zigbee) where transmissions occur with a high degree of spontaneity and the coordination mechanisms are designed for recovery after collisions occur. While simple to implement, contention-based protocols waste energy in packet collisions. We have implemented the Clique-Based Randomized Multiple Access (CRMA) MAC algorithm [2], which employs local proactive coordination in a slotted-time framework so that a node is awake---and consuming energy---for communication only when it has scheduled a time slot with one of its *cliques* (sets of neighboring nodes), significantly improving energy efficiency over contention-based schemes (see [13] and the references therein).

CRMA employs randomized slow time/frequency hopping spread spectrum (SS) at the PHY layer, enabled by tunable-frequency radios. Randomized MAC algorithms for wireless sensor networks are receiving much attention in the research community [6,8,10] due to their good scaling properties. Our approach is unique in that it is integrated with network formation, when clique members share information so they can jointly determine exactly when a communication transaction will occur in the operational phase. However, different cliques use randomized schedules so that they can communicate with little risk of interfering with each other; these schedules are essentially statistically independent since they are based on primarily on measurements of random noise in the hardware. This approach provides CDMA interference mitigation using low-cost hardware, obviates expensive coordination across the entire network via the integrated MAC/

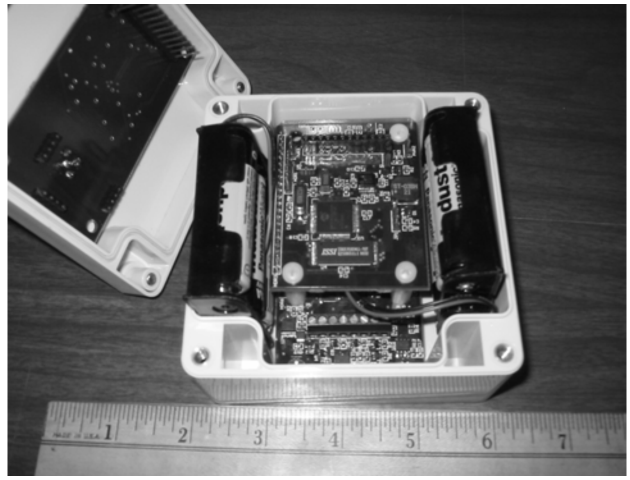

Figure 1. WiSARD hardware. The Brains board (center, between battery packs) controls and receives data from the Radio board (upper left, in box lid) and the Sensor Data (SD) board (bottom).

PHY design, and makes possible extremely large populations of sensors in a single network. It is also robust to electromagnetic interference from other radio-based systems as well as to dynamic variation---fading---of the wireless channel.

A WiSARDNet consists of two types of nodes: a large number of WiSARDs, which can both gather and relay the sensed information, and comparatively fewer WiSARD gateways, which serve as in-network sinks for the information and interfaces to long-haul networks and the internet. Network formation is the automatic, unattended setup of the network that occurs after deployment of the sensors, and consists of route discovery and proactive coordination for access to the shared radio spectrum. The nodes establish cliques with neighboring nodes that most efficiently (in terms of energy consumption and latency) relay information toward a gateway. Our network discovery algorithm operates on-line, so that new routes are discovered under network dynamics, including addition of new nodes and redeployment of existing nodes.

The drivers in integrated or cross-layer wireless network design are often exhibited via the property of *message specificity*. One example is frequency-hopped (FH) versus direct-sequence (DS) SS. Both can provide the necessary excess bandwidth for scalable multiple access. However, there are other considerations that impact the network architecture. While DS provides better instantaneous averaging of interference over a small population of users, FH can provide better robustness to both narrow- and broadband interference (such as a co-located DS network or other wireless service) due to the fact that the desired FH signal can be discriminated for interference more easily and earlier in the receiver. More generally, the specificity of both DS and FH has a disadvantage relative to unspread approaches, in that it forces the use of a beacon-oriented network formation algorithm. Beaconless approaches (e.g., BLESS and its precursors [14]) exploit the non-specificity of the pre-detection wireless signal to use overhearing of operational transmissions for network formation. However, the interference mitigation property of SS via statistical averaging enables a degree of scalability essential in spatially dense networks.

4. HARDWARE

The proof-of-concept WiSARD hardware consisted of two printed circuit boards: a “brains” board and a radio board that it controlled. The brains board also scheduled the probe sampling events and performed the sampling and analog-to-digital (A/D) conversion tasks.

The prototype second generation (G2) WiSARD is an improved design based on lessons learned in the proof-of-concept phase. The major changes are motivated by the demands of increased per-node probe numbers and types, sampling rate, processing power and flexibility.

The functional heterogeneity of WiSARD and gateway nodes is supported by a modular hardware/software architecture. The hardware design is a three-board stack (Figure 1), with the sensor data (SD) (data acquisition) board used in WiSARDs replaced in gateways by a board that provides communication interfaces, global time acquisition, and non-volatile memory for data archival.

A hardware functional block diagram of the G2 WiSARD is shown in Figure 2. To meet the needs of high performance sensing, it is based on a dual-processor design, with the labor divided between a brains board that serves as the network node and the SD board that handles the details of the sensing tasks.

The Brains and SD boards are controlled by commodity microcontrollers; the Brains board employs a Microchip PIC18LF8720 while the the SD board uses a lower-cost PIC18LF452. Both WiSARDs and gateways use a common radio board designed around a Texas Instruments TRF6900 850-950 MHz transceiver chip with an on-board digital frequency synthesizer and controllable transmit power.

4.1. Brains Board

The brains board’s major tasks are the real-time implementation of the communication and networking protocols, controlling the operation of the other boards in the stack, management of the energy supply, and providing the human/network interface.

Memory architecture - The Brains board has a three-level memory structure consisting of the on-chip Static Random Access Memory (SRAM), an off-chip SRAM, and non-volatile memories. The PIC18LF8720 microcontroller has an on-chip SRAM of 3840 bytes for data. The access time is minimal but the size is limited to use for system stacks and temporary storage for computations.

The off-chip 256KB SRAM is used to buffer locally sensed data and messages from other WiSARDs. A parallel interface is employed to provide high speed for frequent memory access.

Non-volatile memories are used for two major functions. The first function is to store important system information such as time and network information. To provide high write cycles and low power consumption, a Ferroelectric Nonvolatile RAM (FRAM) is used; however, its densities are not as high as in traditional memories; our design accommodates an 8KB FRAM chip. The second function is the archival of local probe data as insurance against failures; a low-cost 2 MB FLASH memory is used for this purpose. Because the non-volatile memories are accessed relatively infrequently, a Serial Peripheral Interface (SPI) bus protocol is used to conserve pins. The SPI bus is a 3-wire half-duplex serial communication interface commonly used between microcontrollers and peripheral devices.

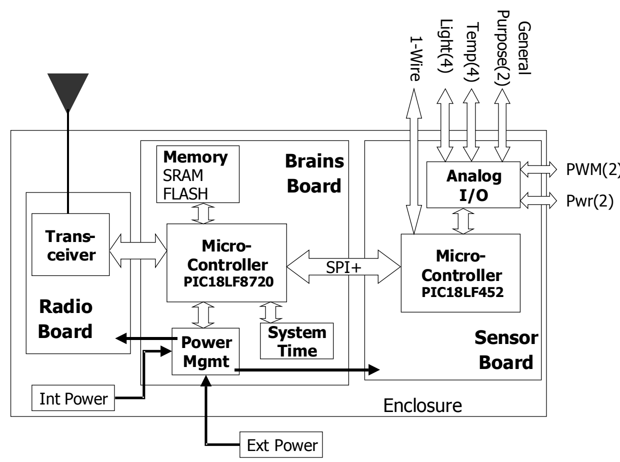

Figure 2. Functional hardware block diagram of the WiSARD sensor. SPI+ denotes an SPI bus augmented with flag and control signals.

Energy management - The G2 WiSARD can handle both internal batteries and an external power supply. It can use one or two internal packs of 3 AA batteries as the power source, depending on required energy capacity. This also allows battery pack replacement without loss of power. External power can range from 2.2 to 16 V, enabling the use of alternate energy supplies such battery-backed photovoltaic panels. Dynamic management of external power admits on-line field deployment of additional power sources to heavily loaded nodes, such as gateways. Integral hardware support for auto-switching to/from external supplies is provided, with status notification to software.

Human/network interface - To support debugging and diagnostics, the WISARD interface includes a buzzer, a pushbutton, a serial port, and an optional LED. The LED requires minimal software support, but requires a special debugging cable. The software-controlled buzzer, similar to units used in cell phones, is superior to an LED for field applications since it is an on-board surface-mount device requiring no additional connections, requires no penetration of the enclosure, does not suffer from washout by sunlight, and draws similar power.

An externally-accessible serial port-based software interface is provided for manual commanding, diagnostics, and data collection from a PC. In addition, a pushbutton is available for hardware-based commands; it is currently used to command the WiSARD to switch modes. We have developed an array of PC-based tools for the project; as of this writing, a comprehensive GUI-based tool for network monitoring/control and data acquisition is in the alpha phase of development.

WiSARD system bus - The interface between the Brain and peripheral boards, currently used by the SD board, consists of a standard SPI bus augmented by several additional pins for flags and control signals. The brains board is also able to shut off the power of the SD board completely to save energy.

4.2. Sensor Data Board

The SD board is designed to manage and control several dedicated probe modalities, and can serve as a controller of an extensible network of wired probes. It has on-board capability to measure four temperature channels via thermocouples that can extend to areas in the vicinity of the WiSARD node, including soil or water at various depths. The SD board also supports measurement of four channels of light intensity using photodiodes. This is provided by current-to-voltage conversion prior to A/D conversion; this circuitry is amenable to other current sensing tasks via a change in passive analog components.

Our design includes a general-purpose analog interface. The current WISARD hardware configuration of this interface supports measurement of soil moisture using active probes based on the measured capacitance of the soil. This capacitance changes as a function of the volumetric water content due to the difference between the dielectric constant of liquid water and dry soil. By changing resistor values, this circuit can also handle other types of active probes.

The active soil moisture probes are driven by auxiliary power outputs in the current configuration, but these outputs can be used for low power output or the switching of high-power signals, such as heaters in sap flow probes.

Two pulse-width modulated (PWM) pins on the microcontroller enable the output of software configurable PWM signals and are available on one of the external connectors. These are designed for new applications, including active probes or environmental actuation devices.

5. SOFTWARE

The receiver sections of our radio-frequency transceiver chips provide only amplification, downconversion, IF filtering, and slicing, requiring that a real-time software radio be implemented on an 8-bit microcontroller. This software radio receiver performs all packet detection, frame synchronization, and bit tracking, in addition to the usual higher-level tasks such as error-control decoding, networking, and network formation. Similarly, the transmitter does the required processing to present a sampled baseband data stream to the radio chip.

WiSARDNet uses a synchronous network architecture that exploits the characteristics of the environmental sensing application: sensing time scales on the order of seconds, all events can be scheduled, and most tasks are relatively simple and can be completed within one MAC time slot.

The WiSARDNet software environment is purposely minimalist. To maximize energy efficiency, we eschew a file system and use only a real-time scheduler. The scheduler explicitly supports slotted-time MAC algorithms and currently implements CRMA. Physical interrupts are reserved for high-bandwidth, clock-driven events required in the PHY layer processing.

The current software implements a master/slave interface between the Brain and SD software so that the SD board can be turned completely off to minimize energy consumption. We are experimenting with various levels of autonomy (ranging from the current master-slave to full symmetric multiprocessing) to achieve minimal energy consumption with good robustness.

6. APPLICATIONS

WiSARDNet was designed from the outset as a system for the monitoring of environmental and ecosystem processes. To assess its performance, we are instrumenting different US sites (in northern California, North Carolina, and northern Arizona) to address three different questions.

Mapping the microclimate of the world's tallest forest - In recent years, development of canopy cranes, walkways, canopy rafts, innovative application of rope techniques, and cable-suspended robots have allowed ecologists to explore the biological wealth and functioning of tropical and temperate forest canopies [7,20,21]. While it is assumed that biological diversity is related to the physical environment, description of microclimatic conditions in forest canopies has been hampered by the logistical constraints of installing and repeatedly accessing conventional wire-based sensing systems. In this application we will study spatial and temporal variation in key microclimatic factors within the crowns of the tallest trees on Earth - the coast redwoods of northern California. Better understanding of microclimatic variation in redwood canopies will aid conservation of remaining stands and restoration of biological diversity in forests recovering from past logging.

The enormous exchanges of water and energy with the atmosphere in redwood forests result in extreme microclimatic gradients. From forest floor to upper canopy, light levels can vary by a factor of 100, air temperature by 15°C, and relative humidity by 50%. Additional fine-scale texturing of microclimate arises from the complex physical architecture of individual redwoods.

While the biological complexity of the redwood forest is evident, its dependence on microclimatic variability is assumed, but not described, because of the difficulty of deploying conventional wire-based sensor networks. We will deploy a 100-node WiSARDNet to map the complexity of microclimate within the crowns of individual redwood trees. A major scientific outcome will be a significant increase in information on moisture and temperature dynamics in canopy environments, specifically in the canopy soils that support much of the biological diversity within temperate rain forest canopies.

Impact of fine-scale ecological disturbances on diversity - Forest diversity depends on environmental variability at a range of scales. Coarse scale gradients in moisture availability and successional changes in light availability exert strong influences on tree performance., in turn influencing spatial patterns. However, at fine spatial and temporal scales, evidence for these mechanisms is weak, despite the fact that local diversity can be high [22,23].

One potential explanation is that current technologies are unlikely to capture how small-scale environmental variation---such as sunflecks---affects plants, and thus previous attempts to document relationships between species diversity and microenvironmental variation have failed. We will use a deployment of approximately 100 WiSARD nodes at two different sites to determine the role of fine scale variability of light, soil moisture, and temperature in the promotion of local species diversity.

Microenvironmental scaling in eddy covariance measurements - Terrestrial ecosystems strongly influence the global carbon and water cycles through photosynthesis, respiration, and evapotranspiration. These fluxes are critical regulators of ecosystem processes, and also influence regional and global climate.

The eddy covariance technique measures turbulent air movements which carry pockets of air upwards, downwards, and sideways. Measuring these in the vertical dimension, and the amount of CO_2, H_2O, and heat they contain, determines the net fluxes across a horizontal plane above the ecosystem. CO_2 and H_2O are measured above the canopy using an infra-red gas analyzer; air temperature is measured using thermocouples; and the wind speed in three dimensions is measured using a sonic anemometer. Fluxes of CO_2, H_2O, and energy are then calculated as the covariance between the respective concentrations and the vertical wind speed.

Eddy covariance is now a standard technique to measure land-atmosphere exchange of CO_2, H_2O, and energy. Other ancillary measurements (e.g., sensible heat flux) are required to demonstrate proper function of the eddy covariance system via an energy balance equation. However, closure within 10-20% has been difficult to achieve (e.g., [9]).

We believe that a major impediment to achieving energy balance closure is that different components of the energy balance are measured on vastly different spatial scales. Specifically, eddy covariance itself captures sensible heat flux and latent heat flux on a relatively large spatial scale - hectares to square kilometers, depending on tower height - whereas heat storage, net radiation, and albedo are typically measured on the scale of, at best, a few square meters. For soil heat flux, the scale is typically even smaller, perhaps 30 cm^2. This issue has never been empirically addressed with a comprehensive spatial array of probes due to the cost and disturbance to the site necessary to install such an array. Wireless sensor network technology removes this constraint, and we will test this idea using a WiSARDNet with an existing eddy covariance system in northern Arizona.

7. EXPERIENCE

In the conceptual stages of the project, a great deal of consideration was given to the use of existing or anticipated wireless networking standards, such as Bluetooth or IEEE 802.15.4. We concluded that an approach that exploits application-driven dependencies across network, software, and hardware layers could yield new levels of energy efficiency. The results to date are gratifying.

Figure 3. WiSARD sensor node deployed on tree trunk. Probe cables are connected at the bottom (behind the antenna).

One aspect that proved to be extremely time consuming was the design and test of the WiSARD physical packaging. Science-quality data requires that probes be external to the node's electronics package, but the resulting enclosure penetrations can compromise resistance to water; thus, providing for probe cables as well as field access for battery replacement in a waterproof yet economical enclosure was a challenge. Our final design for the G2 WiSARD package appears to be a good overall solution. We are using a commercially available waterproof UV-resistant polycarbonate box; we designed our circuit boards to be compatible with the box's integrated mounting bosses, and we machine the boxes with simple holes for the antenna, the thermocouple wires, and a set of waterproof connectors. Battery packs fit in recesses on either side of the circuit board stack (Figure 1). Battery replacement requires the removal of four captured screws on the box lid that seal a perimeter gasket. The boxes have holes external to the gasket that can be used in a variety of ways; for example, a WiSARD can simply be tied to a tree or post using UV-resistant cord, as shown in Figure 3.

8. CONCLUSION

The WISARDNet system is undergoing continuing development. For example, we are integrating 802.11b wireless access into the gateways for the human/network interface, experimenting with the available hardware concurrency, and have developed low-complexity distributed spatio-temporal source coding [24]. We are also extending our network formation algorithms to allow nodes to dynamically choose the gateway that best serves it in terms of latency and energy consumption. Further information can be found at www.mpcer.nau.edu/wnrl/.

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REFERENCES

[1] Cerpa, A., J. Elson, D. Estrin, L. Girod, M. Hamilton, J. Zhao. "Habitat monitoring: application driver for wireless communications technology," 2001 ACM SIGCOMM Workshop on Data Communications in Latin America and the Caribbean.

[2] Flikkema, P. and B. West, "Clique-based randomized multiple access for energy-efficient wireless ad hoc networks," IEEE 2003 Wireless Communication and Networking Conference (WCNC 2003).

[3] Hughes, D., NSF wireless field test project: general project findings, 2002. http://wireless.oldcolo.com/biology/ProgressReports2002/Progress%20Reports2002/57FinalProgressReport(10-26-02).htm

[4] Mainwaring, A., J. Polastre, R. Szewczyk, D. Culler, and J. Anderson. "Wireless sensor networks for habitat monitoring," Proc. First ACM International Workshop on Wireless Sensor Networks and Applications, 2002.

[5] Min, R., M. Bhardwaj, S.-H. Cho, A. Sinha, E. Shih, A. Wang, and A. Chandrakasan. "Low-power wireless sensor networks," Proc. VLSI Design 2001.

[6] Mergen, G. and L. Tong, "Random scheduling medium access for wireless ad hoc networks," Proc. IEEE 2002 Military Comm. Conf. (MILCOM).

[7] Moffett, M. W. and M. D. Lowman. "Canopy Access Techniques," pp 3-26 in Lowman, M.D. and N. M. Nadkarni, eds. *Forest Canopies*. Academic Press, San Diego.

[8] Rozovsky, R. and P. R. Kumar, "SEEDEX: A MAC protocol for ad hoc networks," Proc. MOBIHOC 2001, pp. 67-75.

[9] Sakai, R. K. , D.R. Fitzjarrald, and K.E. Moore, "Importance of Low-Frequency contributions to Eddy Fluxes observed over rough surfaces," *Journal of Applied Meteorology* 40:2178-2192.

[10] Sohrabi, K. and G. J. Pottie, "Performance of a novel self-organization protocol for wireless ad hoc sensor networks," Proc. IEEE 50th Vehic. Tech. Conf., pp. 1222-1226, 1999.

[11] Toh, C.K., "Maximum battery life routing to support ubiquitous mobile computing in wireless ad-hoc networks," *IEEE Communications Magazine*, June 2001, pp. 138–147.

[12] West, B., P. Flikkema, T. Sisk and G. Koch, "Wireless sensor networks for dense spatio-temporal monitoring of the environment: a case for integrated circuit, system, and network design," Proc. 2001 IEEE CAS Workshop on Wireless Communications and Networking.

[13] Ye, W., J. Heidemann and D. Estrin. "An energy-efficient MAC protocol for wireless sensor networks," Proc. IEEE INFOCOM 2002.

[14] Levis, P., *et al.*, "The Emergence of Networking Abstractions and Techniques in TinyOS," Proc. NSDI '04, pp. 1–14.

[15] Levis, P. and D. Culler, "Maté: A Tiny Virtual Machine for Sensor Networks," Proc. 10th Int'l Conf. on Architectural Support for Programming Languages and Operating Systems (ASPLOS X).

[16] Cheong. E., *et al.*, "TinyGALS: a programming model for event-driven embedded systems," Proc. 2003 Symp. Appl. Computing, Melbourne, Florida.

[17] Pottie, G., and W. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, vol. 43, pp. 51-58, 2000.

[18] Estrin, D., L. Girod, G. Pottie, and M. Srivastava, "Instrumenting the world with wireless sensor networks," Proc. Int'l Conf. on Acoustics, Speech and Signal Processing, 2001.

[19] Singh, S., M. Woo, and C. Raghavendra, "Power-aware routing in mobile ad hoc networks," ACM/IEEE Int. Conf. on Mobile Computing and Networking (Mobicom 98).

[20] William J. Kaiser, W., *et al*., "Networked Infomechanical Systems (NIMS) for Ambient Intelligence," in CENS Technical Report #31, UCLA Center for Embedded Networked Systems, 2003.

[21] Koch, G. W., J. S. Amthor, M. L. Goulden, "Diurnal patterns of leaf photosynthesis, conductance, and water potential at the top of a lowland rain forest in Cameroon: measurements from the Radeau des Cimes," *Tree Physiology* 14:347-360, 1994.

[22] Hubbell, S. P., *The Unified Neutral Theory of Biodiversity and Biogeography*, Princeton University Press, Princeton, New Jersey, USA, 2001

[23] Clark, J. S. *Models for Ecological Data*. Princeton University Press, Princeton, New Jersey, USA (in press).

[24] Flikkema, P., B. West and B. Ruggeri, "Network-aware lossless source coding of spatio-temporally correlated sensor data," Proc. IEEE Circuits and Systems Workshop on Wireless Communication and Networking, Pasadena, CA, 2002.