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Wireless Sensor Networks for Ecology

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Field biologists and ecologists are starting to open new avenues of inquiry at greater spatial and temporal resolution, allowing them to "observe the unobservable" through the use of wireless sensor networks. Sensor networks facilitate the collection of diverse types of data (from temperature to imagery and sound) at frequent intervals—even multiple times per second—over large areas, allowing ecologists and field biologists to engage in intensive and expansive sampling and to unobtrusively collect new types of data. Moreover, real-time data flows allow researchers to react rapidly to events, thus extending the laboratory to the field. We review some existing uses of wireless sensor networks, identify possible areas of application, and review the underlying technologies in the hope of stimulating additional use of this promising technology to address the grand challenges of environmental science.

Keywords: spread-spectrum wireless, acoustic and visual data, environmental monitoring, spatial and temporal scales, sensors and sensor technology

Set high in the mountains of northern Taiwan, Yuan Yang Lake has been capturing the attention of scientists for more than 60 years. The subtropical lake, nearly untouched by humans because of its remote location, experiences typhoons each year and is surrounded by an ancient cypress forest—fertile ground on which limnologists, botanists, and climatologists can conduct long-term studies of its rich environments and ecosystems. A single typhoon can drop more than a meter (m) of precipitation on the 4.5-m-deep lake, doubling its volume in a single day and resulting in rapid flushing. The impacts of this extreme flushing on carbon dynamics, when compared with the dynamics in lakes with longer water retention times, can provide new insights into the effects of extreme events on carbon loading (Kratz et al. 1997, Hanson et al. 2003).

However, the very features that make the lake an attractive study location also make it a challenging place to conduct research. It is distant from laboratories and other research facilities, and the frequent typhoons can render it completely inaccessible for extended periods. For this reason, a multidisciplinary team of scientists from the North Temperate Lakes Long Term Ecological Research (LTER) project, the University of California–San Diego, Taiwan's Academia Sinica Institute of Botany, the Taiwan Forestry Research Institute, and the Taiwan National Center for High-performance Computing constructed a global lake-monitoring network, the first of its kind, by establishing wireless connections to sensors in Yuan Yang Lake and several lakes in northern Wisconsin. Within a year of starting the collaboration, a persistent wireless sensor network was in place, in time for the researchers—without leaving their labs, whether in Wisconsin or Taiwan—to observe the rapid deterioration of Yuan Yang Lake's thermal structure (figure 1) and changes in precipitation, wind speed, and barometric pressure during the first typhoon of the season.

This is just one of many examples of how wireless sensor networks are being used to change ecological and environmental sampling—a shift that implements technologies capable of acquiring data at scales that were previously impractical to sample, or of sampling at times that previously

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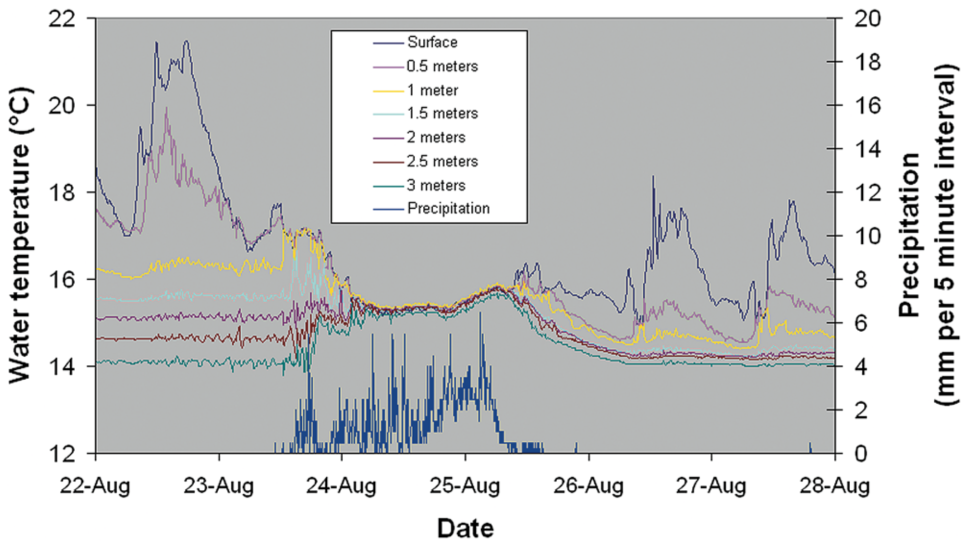

Figure 1. Water temperature at different depths (in degrees Celsius) and precipitation (in millimeters per 5-minute interval) on Yuan Yang Lake, Taiwan, over a 7-day period. An instrumented buoy transmitted these data shortly after a typhoon that dropped 817 mm of rain over a 2-day period. The water column became isothermal and mixed during the typhoon event, potentially resetting the planktonic communities in the lake. Roads leading to this mountain lake are often washed out and impassable for up to several weeks after a typhoon, making manual sampling difficult.

would not have been possible. Consider the following applications of wireless sensor networks to field biology and ecology:

- An ecosystem ecologist collects data from 30 meteorological and streamflow stations located throughout an area of 1760 hectares (ha) in 1 minute instead of the 2 days it takes to hike to each of the sensors (see *http://fs.sdsu.edu/kf/news/view/index.php?id=0021*).
- A stream biologist uses data from upstream flow sensors to increase the collection rate of downstream samplers so that the impact of a full flood cycle on stream chemistry can be assessed at the peak of the flood.
- A wildlife biologist in Michigan conducts a spring bird survey at the Green River Forestry Camp in northern New Brunswick (Gage and Miller 1978) using a sophisticated system of networked acoustical sensors with over 100 acoustic sensors covering 20 listening posts in five forest types.
- A technician replaces a failing oxygen sensor within hours of the failure of its predecessor, thus avoiding the loss of data for a month or more.
- A botanist in Switzerland, seeking to understand why the color distribution of the bush monkeyflower (*Mimulus aurantiacus*) is changing so quickly, studies the interaction of hummingbirds with the flowers in San Diego County—without leaving his office (see *www.npaci.edu/online/v6.8/HPWREN.html*).
- A graduate student counting plants in a permanent plot uses an online key to aid in plant identification and confirms difficult identifications through a videoconference link to an advisor.

Each of these examples illustrates how wireless sensor networks—which comprise wireless network technology coupled with sensors, data loggers, and information technology—are "emerging as revolutionary tools for studying complex real-world systems. The temporally and spatially dense monitoring afforded by this technology promises to reveal previously unobservable phenomena" (Estrin et al. 2003, p. 8). Wireless sensor networks are extending current capabilities and will allow researchers to conduct studies that are not feasible now. Some of the data-gathering capabilities that these networks make possible include the following:

- Sampling intensively over large spatial scales (e.g., multiple watersheds, lake systems, and old-growth forest stands), which otherwise would not be feasible even with an army of graduate students

- Making high-frequency observations that create voluminous data streams
- Collecting new types of data, such as sounds, still images, and video, providing new insights on processes
- Observing phenomena unobtrusively (e.g., viewing cryptic or secretive animals, capturing events not possible before without imposing impacts on the local environment)
- Observing under extreme conditions, such as during typhoons or hurricanes, without endangering the lives of the researchers
- Reacting to events as they unfold (e.g., to change sampling rates, to begin experiments after soil moisture has reached a threshold, to make direct observations of a detected new species, or simply to repair the sensor or data logger without losing months of data)
- Extending the laboratory to the field by enabling researchers in the field to connect with resources in labs around the world to confirm the identification of new species
- Removing distance between the researcher and observational sites

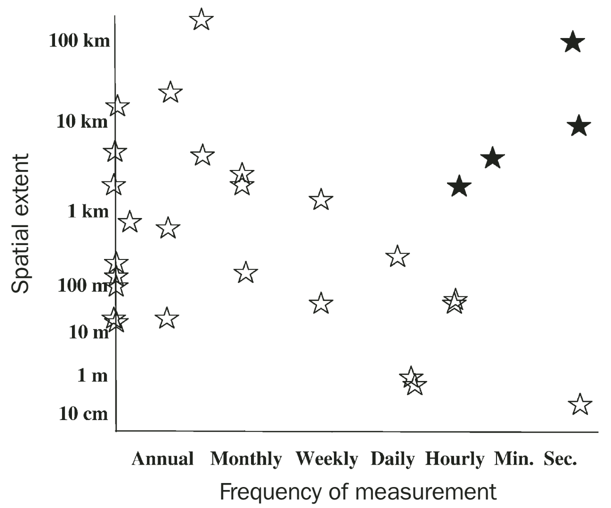

Figure 2. Results from analysis of 52 papers randomly chosen from the journal* Ecology *in 2003 and 2004. Twenty-five papers contained information on both spatial extent and frequency of sampling (open stars). Stars overlapping the y-axis indicate one-time sampling. Data from wireless sensor networks discussed in this article are represented by filled stars. Currently, and without sensor networks, most ecological data are collected either in small areas or at a low frequency. Wireless sensor networks allow data to be collected both frequently and over large spatial extents.

Wireless sensor networks will fill in areas of the space–time sampling continuum in ways that are not possible or not currently practiced today, helping researchers better understand spatial and temporal variation in biological processes, which is central to ecology and the environmental sciences (Cowling and Midgley 1996, Burke and Lauenroth 2002, Kratz et al. 2003). A survey of 52 papers chosen randomly from the journal *Ecology* illustrates that most ecological sampling is conducted at small spatial scales or consists of infrequent or one-time sampling (figure 2). Wireless sensor networks can fill a gap in current capabilities by enabling researchers to sample over distances or at rates not currently possible. It is exactly this range of space and time (widely distributed spatial sensing with high temporal frequency) that will be critical to address the "grand challenges of the environmental sciences" (biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, hydrologic forecasting, infectious disease and the environment, institutions and resource use, land-use dynamics, reinventing the use of materials) proposed by the National Research Council (NRC 2001).

The use of wireless sensor networks by ecologists is in its infancy. In this article we describe the potential application of wireless sensor networks to supplement traditional approaches to ecological research, including long-term analysis, comparison, experimentation, and modeling (Carpenter 1998). We give an overview of wireless (spread-spectrum) technology; provide examples of how this technology, integrated with sensors, data loggers, and information technology, is enabling new types of ecological studies; and examine challenges to be addressed for wider deployment of these systems.

We organize the topic of wireless field sensors along two related axes, discussing the coevolution of sensor networks and the science questions that go with them. The axis of sensor technology and wireless communication has reached beyond its origin in military and computer networking to applications in environmental sensing. Use of sensor networks has allowed researchers to expand the axis of scientific inquiry to include spatiotemporal scales that were previously difficult to study. In this article, we emphasize the axis of scientific inquiry as it relates to the study of ecosystems. There are rich research challenges still being faced in wireless sensor networks (Estrin et al. 2003) and several practical considerations in implementing such a network.

The basic wireless sensor network

The "network" component of a sensor network can take many forms and incorporate a variety of means of transmitting data from wires to cellular telephones and to microwave radios (Berger and Orcutt 2002, Estrin et al. 2003, Yao et al. 2003). However, because many field biologists and ecologists operate in areas far distant from conventional communication infrastructure (telephone lines and cellular towers), we focus on using commercially available, license-free, (spread-spectrum radios), coinvented by actress Hedy Lamarr and composer George Antheil in 1941, remained classified until the mid-1970s, with the Federal Communications Commission (FCC) first issuing rules on its use in 1985. Early spread-spectrum radios were expensive, proprietary, and not well suited to field use. However, they have become increasingly accessible to biologists, in large part because of their wide use in office-based wireless networks and the development of communication standards that allow radios from different manufacturers to intercommunicate.

Conceptually, a wireless sensor network can be divided into a set of intercommunicating layers (figure 3). Interacting with the environment is the sensor layer. Sensors respond to changes in their environment by producing an electrical signal. Most frequently this is a change in voltage, current, or frequency. Sensors now in common use measure biologically important physical parameters, such as temperature, humidity, precipitation, wind, soil moisture, and ground- and streamwater levels. Less commonly used are chemical sensors, which measure carbon dioxide, pH, and oxygen levels. Also available are image and audio sensors that allow biologists to unobtrusively observe organisms and ecological systems.

In the field computation layer, converting the signal from the sensor into a digital form is the role of processors, most frequently in the form of specialized data loggers. Data loggers convert the changes in current and voltage generated by the sensor into digital data and store it for later retrieval, providing a way to communicate data over standard serial and

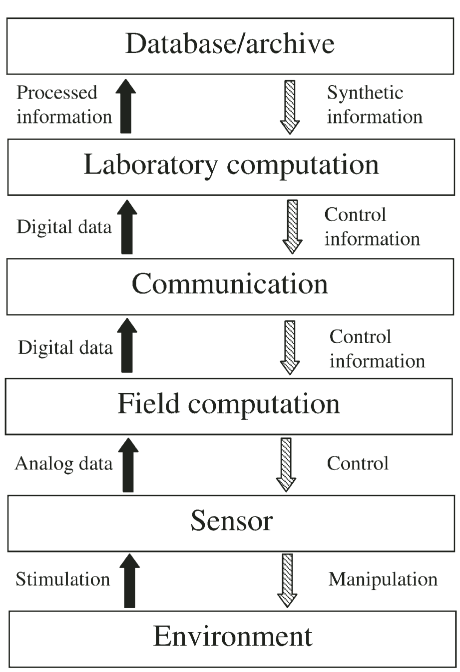

Figure 3. Component layers of a wireless sensor network. In some cases multiple layers may be encompassed in a single device; for example, sensor, field computation, and communication equipment may be packaged in a wireless data logger with an integral temperature sensor.

Ethernet interfaces. Data loggers vary widely in price and capabilities. A simple logger is preprogrammed in the factory to work with a specific sensor. A more complex and expensive logger includes a programming language that allows it to be customized to support different kinds of sensors. Custom-built processing capabilities can be built around "embedded processors," essentially personal computers (Delin 2002, Vernon et al. 2003, Woodhouse and Hansen 2003, Yao et al. 2003). For specialized types of data, such as images, the sensor and processor are often contained in the same unit. For example, a "network camera" incorporates lens, photosensor, analog-to-digital converter, image memory, and a processor running a Web server, all in a single unit.

The communication layer can be either wired or wireless, but for most field biologists or ecologists, the "last mile" to the study site is likely to be wireless. Modern network radios are based on digital spread-spectrum communications. Spread-spectrum radios simultaneously use weak signals on many different radio frequencies to transmit data, in contrast to traditional radios, which use a strong signal on a single radio frequency (Peterson et al. 1995). The principal reasons for using spread-spectrum radios are that they have high bandwidth (a measure of the volume of data that can be communicated in a given time period), require relatively little power, incorporate error-correction functions to eliminate transmission errors, and usually do not require a license. They are also inexpensive, with many units costing less than $100.

Serial spread-spectrum radios act essentially like a long serial cable linking laboratory computers and field processors. Like a serial cable, they carry only one data stream at a time, typically at a data rate of 0.115 megabits (Mb) per second (s). By having a master radio automatically switch between slave radios, data streams from multiple instruments can be captured. Figure 4 shows a simple buoy network using serial radios. In contrast, Ethernet-based spread-spectrum radios break data streams into "packets," thus allowing simultaneous communications with a large number of devices at high rates of speed (from 11 to more than 108 Mb per s). The "Wi-Fi" (wireless fidelity) networks that are ubiquitous on university campuses are Ethernet-based (802.11a, 802.11b, 802.11g) spread-spectrum radios.

The range of license-free spread-spectrum radios depends to a large degree on the terrain, vegetation, elevation, and power levels used. The range of "out-of-the-box" Wi-Fi radios is roughly 200 m. However by adding towers, directional antennae, and amplifiers, their range can be extended to 75 kilometers (km). The most commonly used frequencies are those that can be used without a license: 900 megahertz (MHz), 2.4 gigahertz (GHz), and 5.8 GHz. These frequencies all require line-of-sight communications, and some (such as 2.4 GHz) can easily be blocked by vegetation.

In the laboratory computation layer, once the data have been transferred from the field to the laboratory or office, they need to be further processed into human-readable forms such as graphs and tables. Additionally, in the database–archive layer, data can be stored in databases for future use. The high rate of speed most sensors and wireless networks can attain poses challenges for managing large data streams.

The flow of information from the environment to the database is not unidirectional (figure 3). Archived data can be used to produce synthetic products that may dictate the way sensors are used (e.g., increasing sampling rates during circumstances deemed "unusual" based on archived data). With some types of robotic sensors, the environment can be manipulated to facilitate field experimentation.

Applications of wireless sensor networks

Here we use real-world examples to demonstrate four main advantages of wireless sensing networks: high-temporal frequency sampling and analysis, spatially dense and extensive sampling, unobtrusive observation, and the shared use of a common wireless infrastructure by many diverse but related projects working at the same study site. Collectively, these vignettes show how deployments of wireless sensing systems (a) can facilitate reliable and relatively inexpensive data collection; (b) allow for data collection at times when it would be inconvenient or dangerous for field personnel to make manual measurements; (c) can be used to observe phenomena at greater temporal and spatial grain and extent than was previously possible; and (d) are being used to realize scientific goals.

High-frequency observations. Aquatic systems can play important roles as conduits of inorganic carbon from terrestrial systems to the atmosphere and as mineralization sites of organic carbon (Cole et al. 1994). Research on specific processes affecting the carbon dynamics of lakes, such as gross primary production and respiration, traditionally has required time-consuming, labor-intensive, and relatively infrequent sampling, especially for remote lakes (Kratz et al. 1997). Using wireless communications to instrumented buoys (figure 4), scientists at the North Temperate Lakes LTER site in Wisconsin have been able to make high-frequency measurements of dissolved oxygen, water temperature at various depths, downwelling radiation, and wind speed from multiple lakes. The high-frequency data on dissolved oxygen, supported by thermal and meteorological data, can be used to make daily estimates of gross primary production and respiration (Hanson et al. 2003).

A series of solar-powered instrumented buoys equipped with these sensors make measurements every 5 to 10 minutes. The data are transmitted every hour, using spread-spectrum digital radios, to a base station where the data are processed and published in a Web-accessible database. With the network of limnological buoys, scientists have begun to assess important physical and biological changes in lakes that occur on scales ranging from minutes to months. The questions have evolved in scale from seasonal (e.g., under what conditions are lakes net sources of carbon to the atmosphere?) to weekly (e.g., how does lake metabolism respond to episodic driving events, such as thunderstorms or typhoons?) and finally to minute or hourly scales (e.g., under what conditions do physical, rather than biological, processes drive observations of dissolved oxygen dynamics?). At the seasonal scale, a mobile network of deployable buoys was used in a comparative study of 25 lakes, which found that the balance between total phosphorus and organic carbon load determines whether gross primary production outweighs respiration (Hanson et al. 2003). At the weekly scale, one of these buoys was used to assess the impact of a rare and cataclysmic event on the small Yuan Yang Lake in Taiwan. Here, a typhoon raised the lake level by more than 2 m, doubling its volume and mixing the water column (figure 1). At the scale of minutes, we have been observing the effects of physical processes, such as wind-driven internal waves and vertical or horizontal mixing of water, on dissolved oxygen dynamics near our sensors. Work is ongoing to couple field measurements with a near-real-time, three-dimensional nonhydrostatic model of lake circulation to gain an understanding of whole-lake carbon cycling under a variety of physical conditions. This increased capability will allow the development of intelligent software programs (i.e., agents) to analyze data streams in near-real time to separate biologically and physically driven changes in dissolved oxygen, and enhance understanding of carbon dynamics in lakes at time scales from minutes to months.

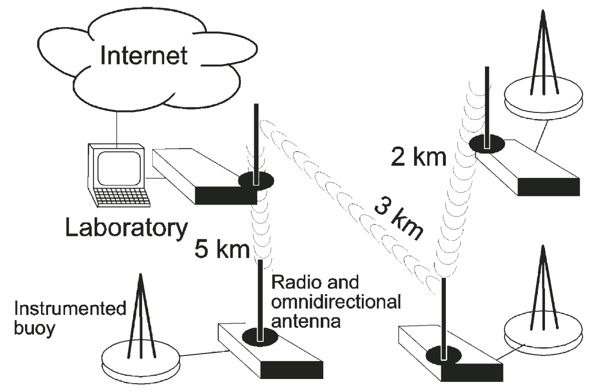

Figure 4. Diagram of the instrumentation for a wireless sensor network. Serial digital spread-spectrum radios are used to connect instrumented buoys to the laboratory. Individual buoys are polled sequentially by a master radio located at the laboratory. One unit acts both as a slave radio and as a relay. The antenna at the laboratory is located on a tower to help penetrate vegetation. All radio links are at 0.115 megabits per second and 900 megahertz.

Intensive and extensive sampling. In arid southwestern watershed ecosystems, water input and flow are crucial ecological features that underpin many ecological processes. Understanding water balance in these spatially patchy ecosystems requires multiple sampling locations that cover large areas. However, steep topography, lack of roads, and extreme temperatures make manual collection of data a daunting task. To circumvent those challenges, researchers at the Santa

Margarita Ecological Reserve (SMER) use a wireless infrastructure as part of a "wireless watershed project." A growing and dense network of 32 weather- and water-monitoring stations deployed at SMER couple visual imagery with standard meteorological and hydrological measurements to allow near-real-time analysis of water dynamics throughout the watershed. A few winter storms in this watershed, which can change water levels by several feet in just a few hours, produce a dominant portion of discharge, sediment, and chemical transport. These data are being used to drive watershed models that are linked to hydrologic and meteorological sensor data (Cayan et al. 2003). Furthermore, with the equipment that is now part of the sensor network, researchers can begin to understand the impact of the microclimate in the Santa Margarita watershed, a microclimate that involves the regular occurrence of a marine layer. Researchers are using the SMER array to study how and when this marine layer transitions to the continental air mass, and how it affects the vegetation and ecosystems of the watershed.

The wireless network allows data retrieval from the weather- and water-monitoring stations to occur in near-real time and without the labor that would be required to make regular manual visits to the 32 sites in this remote and topographically challenging area. In addition, the wireless network provides an infrastructure that can be extended to other sites and sensors within the study area. Using this wireless infrastructure, researchers, educators, and habitat managers can integrate their own research data with nonproprietary real-time and archived ecological data from SMER.

Unobtrusive observations. A challenge for researchers working with animals, birds, and fish is that the physical presence of the researcher can alter the behavior of the organisms under study. This problem is exacerbated if a large number of research locations need to be visited, as the time for organisms to become acclimated to the presence of the observer becomes commensurately short. A major advantage of wireless sensor networks is that observers can be located at a great distance from the phenomenon being observed. Here we give an example in which unobtrusive sampling using wireless sensor networks allows for near-real-time observations that would be affected by the presence of the observer.

Sound has long been used by ecologists as a means of assessing the presence of a species and its abundance. Through repeated measurement at the same location, researchers can produce maps of the home range of bird and amphibian species, for example. Repeated annual measures of the sound of birds along fixed transects has produced one of the most significant long-term, regional-scale biological surveys in North America (Robbins et al. 1986). In addition to its application as a means to survey animals such as birds, bats, amphibians, and ocean mammals (Moore et al. 1986), sound is an attribute that can be used to measure other environmental features, such as precipitation intensity, soil wetting, and atmospheric turbulence. Sound is also of value in assessing human sounds created by transportation vehicles, such as airplanes, or by vehicles associated with recreational activities (e.g., all-terrain vehicles, jet skis, and snowmobiles; Gage et al. 2004).

One challenge in conducting sound-based studies is that a human listener can be in only one place at a time, and the presence of a human can alter the soundscape. Fortunately, the microphone is a sensor that can readily be deployed using wireless technology. Synchronous, multipoint acoustic networks can enable researchers to assess the abundance and distribution of organisms using triangulation to pinpoint the location of individuals, and thus determine the location of signaling individuals in complex habitats using three-dimensional arrays. The use of wireless technology enables the placement of microphones in locations where wired technologies would disrupt the ecosystem. Wireless technologies also can provide the required versatility of quickly setting up arrays of acoustic monitoring networks to assess sounds over short time intervals—an approach infeasible with complex wired infrastructure.

In one example, computers are used to automatically collect acoustics at half-hour intervals and transmit the sounds of the environment to a distant server in the Remote Environmental Assessment Laboratory, where they are stored and analyzed. The results and sounds are placed in a digital library (*http://envirosonic.cevl.msu.edu/acoustic*). Contrasting ecological settings and their associated sonograms have substantial qualitative differences.

Experience in using wireless communications to transmit acoustics has provided incentives to continue with some of the more challenging aspects of collecting and analyzing real-time acoustics. With an operational monitoring network, ecological change can be studied through the realization of the following capabilities: the ability to determine the time and type of event (first arrival of migrant birds, first amphibian breeding calls, first boat traffic, gunshot); the identification of species in ecosystems (birds, amphibians, insects); the survey of abundance of organisms (birds, amphibians); the relationships between sound and physical measurements (chemical, meteorological); the measurement of ecosystem disturbance (physical, chemical, acoustical); the incidence of human activity; and the interpretation of the environmental symphony. The measurement of sound at fixed locations over time can provide additional knowledge about daily, seasonal, and annual sound cycles in ecosystems, as well as the ability to compare acoustic signatures in different locations.

Scalable infrastructure for multiple goals. Once the wireless communication infrastructure is in place, multiple researchers or user groups can take advantage of the wireless network. Three examples of how wireless infrastructure can serve multiple users are the Virginia Coast Reserve (VCR) LTER project; the High Performance Wireless Research and Education Network (HPWREN) in San Diego, Riverside, and Imperial Counties, California; and the Ecogrid project in Taiwan.

The goal of the VCR LTER project is to understand the relationships between physical, biological, and anthropogenic forces on the dynamic ecology of a system consisting of coastal barrier island, lagoon, and mainland elements (Hayden et al. 1991). Measurements from Hog Island, a low-lying barrier island, include long-term, hourly meteorological, groundwater-level, and tidal data. These are coupled with measures of disturbance and landscape change, topographic surveys, changes in primary production of grasses and shrubs, and studies of nutrient dynamics to discern ecological patterns and the processes that drive them (Oertel et al. 1992, Hayden et al. 1995, Young et al. 1995, Christian et al. 1996, Brinson and Christian 1999, Day et al. 2001).

An Ethernet-based wireless network backbone extends from the VCR LTER laboratory to the barrier islands, 20 km off the Virginia coast. Initial use of the network was for a pan–tilt–zoom network camera, which has generated a database of over 330,000 images (*http://ecocam.evsc.virginia.edu/html/index.php*) for research and educational use. With the addition of serial-to-Ethernet converters, that use rapidly expanded to include collection of data from meteorological and tide stations. Subsequently, a NASA (National Aeronautics and Space Administration) polarimetric radar station was added to the wireless network. Most recently, a boat equipped with a network access point (with relay to the Internet via the island towers) provides network access to researchers in the vicinity of the boat. A flux tower and soil nitrogen system, each with potential throughputs in the range of gigabytes per day, will be added soon.

Having the network in place has dramatically reduced the data losses associated with sensor failures, since researchers need not wait until the end of the month to learn of a problem. It also saves a 40-km boat ride by a technician to retrieve the data from the stations, allowing her to focus instead on maintenance and repairs and other research projects. Cameras allowed researchers and students alike to observe storm flooding during Hurricane Isabel in 2003 (figure 5). The cameras have been used to unobtrusively identify tagged peregrine falcons that perch on the towers where cameras are located. In the Virginia Ecocam project, students are taught techniques of ecological enumeration using "crabcams" that use image-processing tools to help provide counts of fiddler crabs (*Uca pugnax*) at different tidal phases and under different weather conditions. These cameras also serve as "fishcams" during high tides. Finally, students can observe the nesting heron colonies using a "birdcam."

The HPWREN project supports collaborations among field researchers, network engineers, and crisis management officials in southern California (Woodhouse and Hansen 2003). These collaborations have allowed the project to use real-time sensor networks in a regional wireless setting and enhance collaborations between diverse users (Vernon et al. 2003). Examples include the SMER wireless watershed project described above; earthquake sensing, in which the challenge is to ensure that sensors are adequately configured to withstand a catastrophic seismic event; astronomical data, moved wirelessly from the remote observatory to analysis around the world; incident management in the case of wildfires; and rural education for Native American tribes in San Diego County (Harvey et al. 1998, Cayan et al. 2003, Vernon et al. 2003). Crisis management personnel have quickly adopted the use of video cameras deployed as part of the network. Field scientists have also used the cameras for monitoring animals and regional weather conditions. During the 2003 Cedar Fire, in San Diego County, fire officials used the cameras to view the fire, and images and time-lapse animation were shown on national television (*http://hpwren.ucsd.edu/news/041006.html*).

The Ecogrid project provides wireless infrastructure for the six research areas in the Taiwan Ecological Research Network, including four forest sites (Fushan, Guan-Dau-Shi, Ta-Ta-Chia, and Nan-Jen-Shan), one alpine lake site (Yuan Yang Lake; figure 6), and one coral reef site (Kenting; figure 6). These sites differ in geography, geology, climate, and vegetation types, and represent the range of important ecosystems of Taiwan. Fushan lies in the northeastern part of Taiwan and consists of nearly 1100 ha of pristine subtropical forest, a haven for the rare muntjacs and endangered birds that wander among trees that are hundreds of years old. This remote location contains 515 of Taiwan's vascular plant species (TFRI 1989), making it a significant research site for biodiversity studies. Furthermore, the range of altitudes on the island provides amazingly different ecosystems within short distances of one another.

The Ecogrid, facilitated through Taiwan's National Center for High-performance Computing and the Knowledge Innovation National Grid, uses wired and wireless networks to connect the six ecological reserves into a single virtual environmental observational laboratory. It facilitates not only individual field studies but also cross-site collaborations. These collaborations make possible improved understanding of the effects of disturbances such as typhoons, and of geological events such as landslides and earthquakes, on ecosystem structure and dynamics.

This effort has developed tools for connecting sensors and their data loggers through heterogeneous wireless connections (e.g., Yuan Yang Lake and the lake metabolism project mentioned earlier); tools for retrieving images from a database based on shape similarity; and tools for controlling instruments (such as the cameras used to track movement of animals; a mobile robot transports the instruments). The project has also experimented with capturing images underwater off the coast of Taiwan (figure 6). The ultimate goal of the project is to provide ecologists, in Taiwan and elsewhere, with a persistent infrastructure, based on tools of the international grid community, to monitor and study long-term processes at spatial scales that span the island.

Technical considerations and issues

Wireless sensor networks can aid in existing research, but the critical question to ask is "What things will I be able to do in

Figure 5. Images from wireless cameras (a) before and (b) during Hurricane Isabel (18 September 2003). Researchers increased the image sampling rate during the storm from an Internet café in Seattle. The network continued to provide image and meteorological data throughout the storm until a power failure occurred in the mainland laboratory. Photographs: John Porter.

the future that I can't do now?" Once the decision is made to establish a wireless sensor network, the issue becomes how to implement it. Here we review the decisions to be made at each layer (figure 3), with some discussion of additional needs and how they might be met. A Web site (*http://wireless.vcrlter.virginia.edu*) contains additional information on specific components.

At the sensor level, the primary issues are the availability and cost of the sensor, its suitability for deployment in a field environment (with all the hazards, from fouling to theft, entailed in that environment), and its power requirements. Sensors for physical parameters, such as temperature, moisture, light, pressure, and wind, are widely available. Nitrate and carbon dioxide sensors are currently very expensive, have moderate power requirements, and are not robust enough for long-term field use. Other chemical sensors, such as phosphorus and protein sensors, remain in the initial design and development phases and are not available for widespread field use. In contrast to the many available physical sensors (e.g., thermistors and thermocouples) that have evolved over decades and are now small in size, have minimal power requirements, and are robust for long-term field use, many biological sensors are in their infancy. For instance, the capacity to sense individual species is generally not available and must be inferred from other sensors. Similarly, it is not feasible to perform *in situ* DNA analysis in terrestrial habitats, and that capability for aquatic systems remains in the development phase (Estrin et al. 2003). New approaches based on molecular signatures (Caron et al. 2004) or on microchip technologies, such as MEMS (microelectromechanical systems) devices, are addressing these challenges and offer the potential to produce inexpensive sensors in large quantities (Beeby et al. 2004, Maluf and Williams 2004). As sensors enter the marketplace and are adopted for field research, the need for prototyping and test beds will become more immediate. Sensor networks, together with network security and coupled cyberinfrastructure, must be tested and validated across a range of natural conditions, requiring controlled field experiments and comparisons with proven measurement techniques.

For field processing, the major choice is between a traditional data logger and a more sophisticated processor such as an embedded computer or a palmtop computer. Most data loggers are designed with low power requirements in mind. However, not all data loggers are suitable for remote operation. Data loggers that use proprietary interfaces, or require users to push buttons on the logger to retrieve data, may not be suitable for network operation. Alternatively, embedded and palmtop computers can use generic software, but may require additional hardware and custom programming to interface to a sensor, and typically require much more electrical power than data loggers. For this reason, the most common choice is a data logger that has a well-documented interface (thus allowing user-written programs as well as vendor-supplied programs to process the data) and features that support remote control of all critical logger functions. The advent of small, low-power systems that integrate sensors, processors, and communications in a "mote," "pod," or "orb" holds great promise for future biologists (Harvey et al. 1998, Delin 2002, Estrin et al. 2003, Vernon et al. 2003, Woodhouse and Hansen 2003, Yao et al. 2003, Szewczyk et al. 2004).

For communications, a researcher must decide upon the type of network protocol, the frequencies, and the power levels to be used. The two most common interfaces used today are serial (RS-232/RS-485) and Ethernet (802.11a, 802.11b, 802.11g; Wi-Fi). Serial communications typically have a maximum rate of 0.115 Mb per s, which is sufficient for most nonvideo data. In contrast, Ethernet communications support speeds ranging from 2 to more than 100 Mb per s. Serial networks are best used where a limited and predetermined number of sensor locations will be used and high speed is not required. Ethernet-based networks are more flexible and are amenable to ad hoc expansion, but may require serial-to-Ethernet converters to connect to most data loggers.

The choice of transmission power level and frequency is constrained by national laws. The FCC limits unlicensed spread-spectrum communications to the 900-MHz, 2.4-GHz, and 5.8-GHz bands. In Europe and much of Asia, Africa, and South America, the 900-MHz band is not available to the public. All of these frequencies require a clear line of sight, with no hills or mountains obstructing signals. Some frequencies (particularly 2.4 GHz) are easily attenuated by obstructions, especially water. Since leaves are predominantly water, even a thin layer of vegetation is enough to reduce or eliminate some signals. To circumvent these limitations, towers (and even balloons) are used to raise antennae above the surrounding vegetation. Also, hybrid networks that use short-range wired networks between sensors in areas poorly suited to wireless (e.g., dense forests) can be connected to tower-mounted wireless radios for communication. In the future, changes in FCC rules may permit use of wireless networking on bands that are less sensitive to obstruction by vegetation.

The transmission power of radios is a double-edged sword. Most spread-spectrum radios are operated at low transmission power (typically 0.1 watt or less) to reduce their electrical power requirements. High-power radios or amplifiers can go up to the legal power limit, but their electrical power requirements are consequently greater. Using directional antennae, which concentrate a radio signal in a particular direction, is one way to improve range without requiring additional electrical power.

A recurrent theme in this discussion has been the issue of electrical power. Obtaining sufficient electrical power in field situations is often difficult, requiring the use of solar, wind, or water-powered generators. Our joint experience has been that failure of electrical power is the most common cause of network failure. In some cases, power can be saved by using timers or programming data loggers to deactivate the network during times of inactivity. Ultimately, the underlying efficiency of data transmission needs to be increased by using more efficient electronics and incorporating embedded computational resources into the sensors and networks, so that the networks can integrate voluminous raw data into needed data products before they are transmitted back from the field (Estrin et al. 2003).

Infrastructure at the laboratory computation level presents relatively few difficulties, because personal computers, networks, and power are already in place. However, there are still substantial challenges in the area of software. Processing the data flows that can result from a large sensor network with hundreds of sensors has been likened to "drinking from a fire hose." Manual methods of quality control and quality assurance are rapidly overwhelmed, so automated tools and analytic workflows are needed to filter erroneous data (Withey et al. 2001, Ganesan et al. 2003). One solution is to move more of the processing from the laboratory to the field, with intelligent sensors that detect and forward interesting data

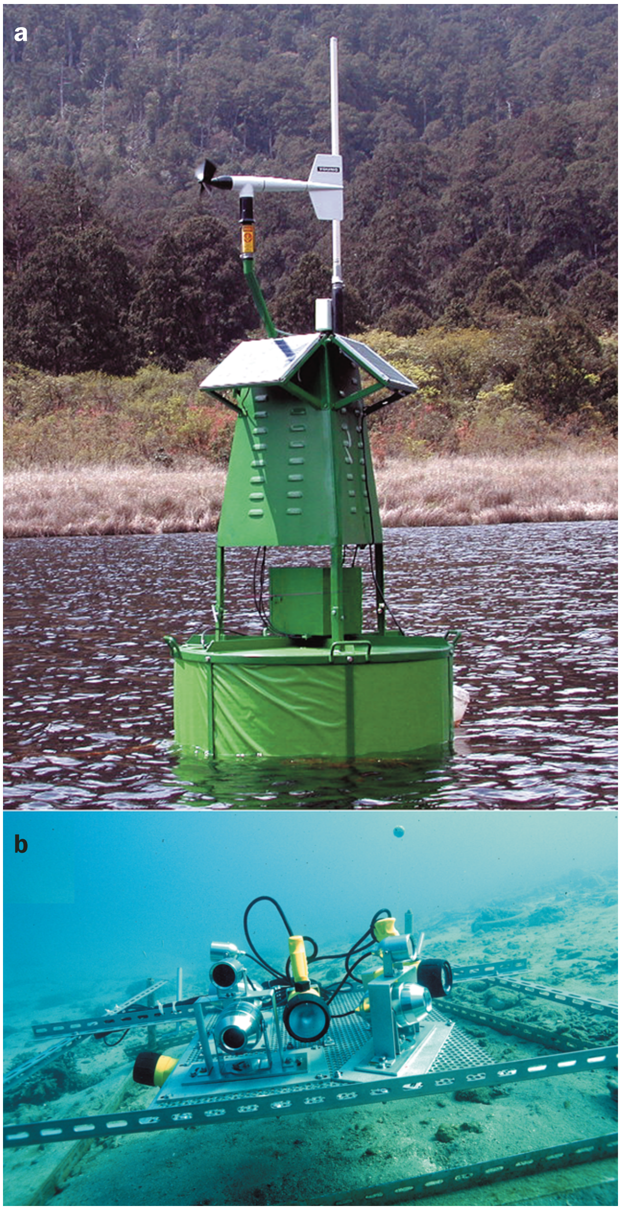

Figure 6. Two examples of wireless sensors. (a) A wirelessly connected buoy on Yuan Yang Lake combines a meteorological station with oxygen and temperature sensors that characterize the water column. (b) On the Kenting coral reef site, infrared cameras and illuminators capture reef fish behavior. Photographs: (a) Alan Lai and (b) Yu-Hsing Liu.

while discarding data that are erroneous or unimportant (Estrin et al. 2003).

Current technologies are sufficient to support the development by biologists of manually configured wireless sensor networks that are relatively small, consisting of tens—not hundreds or thousands—of sensors. Although limited, these networks can generate unique and valuable data for ecologists and field biologists. However, there are still outstanding issues concerning sensors, radios, processors, and cyberinfrastructure that need to be addressed before wireless sensor networks will become ubiquitous in field biology and ecology (Withey et al. 2001, Juang et al. 2002, Estrin et al. 2003, Wooley 2003). For example, self-diagnosis and self-healing are critical requirements for sensor networks and will be essential for relieving users from attending to large numbers of individual sensors in the field. In addition, security solutions that allow users to restrict access to sensitive data, and quality assurance algorithms that ensure continued network operations in the presence of malfunctioning sensor nodes, are required (Estrin et al. 2003). We foresee an evolutionary process in the design and use of biological sensor networks, wherein the enabling sensor network infrastructure stimulates new ideas and concepts of what is possible and, in turn, stimulates new demands for that infrastructure. The requirement for "anytime, anywhere, any speed" will evolve, and researchers will define new imperatives.

The envisioned capabilities of hyperscalable and robust and sustainable sensor arrays require a new genre of cyberinfrastructure and software services to support time synchronization, *in situ* calibration and validation, and programmable tasking, as might be required to increase the sampling rate during an event (e.g., lake turnover, hurricane, or earthquake). New metadata and analysis and visualization tools are also needed (Withey et al. 2001, Atkins et al. 2003, Estrin et al. 2003), including metadata wizards and approaches for automating metadata capture and encoding; new algorithms from statistics and machine-learning fields that can facilitate interpretation of high-bandwidth data streams and better enable knowledge discovery and dissemination; and new visualization capabilities on handheld mobile devices so that results, images, and audio can be provided dynamically to the investigator in the field (Atkins et al. 2003, Wooley 2003). Fortunately, substantial research is being dedicated to these topics. Extant and proposed research entities such as the Center for Embedded Networked Sensing, the Consortium of Universities for the Advancement of Hydrologic Science, Inc., the Geosciences Network, the Collaborative Large-scale Engineering Analysis Network for Environmental Research, the National Ecological Observatory Network, and the Science Environment for Ecological Knowledge, collectively, are or will be supporting research aimed at addressing these challenges.

Conclusions

In determining whether a wireless sensor network provides an advantage over manual data collection or the use of traditional data loggers, researchers need to ask the following questions:

- *Are data from a wide area required?* Networked sensors can drastically reduce logistical costs associated with visiting a large number of locations, and make extensive sensing feasible when it would otherwise not be.
- *Do data need to be collected at high frequencies?* Measurements that generate voluminous data (such as still image, video, audio, or multiple sensors) can overwhelm the storage on traditional data loggers, especially if data are collected at a high frequency.
- *Does data collection need to be unobtrusive?* In some cases, such as behavioral studies, periodic visits to record data or to dump a data logger will change the behavior of the system under study.
- *Are real-time or near-real-time data needed?* Rapid access to data may be required if experimental manipulations are to be pursued; if reducing gaps in data caused by sensor failures is a priority; or if conditions such as fire, flooding, or severe weather imperil the sensor system.
- *Is a bidirectional data flow required?* Targeting measurements of particular phenomena may require flexibility in the frequency and type of measurements, experimental studies may require periodic robotic manipulation, and researchers in the field may require access to data resources available over the Internet.

If the answer to one or more of these questions is yes, then establishment of a sensor network may be justified.

Wireless sensor networks are a new sampling tool for ecologists and field biologists. This tool ushers in a third wave of the "land-based" sampling that began with researchers' expeditions to remote areas to take measurements at a point in time and at a location, followed by the advent of data loggers that would allow researchers to leave collecting devices and return to that point (or set of points) to download information collected at predetermined intervals.

Wireless technology is relatively new in ecology and field biology, but the emergence of a new family of off-the-shelf sensors, data loggers, and communications and computing resources is an enabling technology for a range of sensor networks that can be exploited by biologists. The advent of low-power, small-footprint, affordable devices has made this capability much more available to the ecological community. As we have illustrated in our examples, several groups have deployed these sensor networks to their advantage and are beginning to see benefits from their investments.

There are many technical problems to be overcome in using sensor networks, such as sensor development, network scalability, and power demands, to address the larger scale of "grand-challenge" problems (NRC 2001). New sensors, improved power systems, and scientific information management systems and cyberinfrastructure will ultimately be required. However, our examples with extant technology show that it is possible to conduct research with even simple, cost-efficient deployments of sensor networks and gain scientific insights today.

The multidisciplinary teams used first to implement and then to maintain wireless sensor networks (e.g., HPWREN, Taiwan Ecogrid, the lake metabolism project) are a critical factor in the successful examples described here. These teams have allowed for rapid deployment of systems and a focus on the development of improved systems. Equally important, as the lake metabolism project demonstrates, researchers are no longer constrained by national boundaries when studying exciting phenomena. It is our hope that the examples described here will motivate the scientific community to aggressively experiment with and implement these networks, to expand the problems that can be tackled (filling in areas not currently covered in figure 2), to engage students in this process, and to launch a new era of ecological discovery on processes important to our planet.

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