WiSARDNet FIELD-TO-DESKTOP:
BUILDING A WIRELESS CYBERINFRASTRUCTURE FOR
ENVIRONMENTAL MONITORING

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Abstract - The technology of wireless sensor networks has enabled new levels of spatial coverage and density in the monitoring of variables important in numerous applications, including ecological research and environmental management. These networks are composed of small, energy-efficient devices that wirelessly collaborate to gather data on temperature, light, soil moisture, sap flux and other variables over space and time. However, a complete monitoring solution requires the conversion of this data to useful information for a user who may be anywhere in the world. To address this challenge, we have designed a complete Field-to-Desktop system for the acquisition, storage, and visualization of environmental data from a wireless sensor network using industry-standard networking, database, and web development tools. This paper describes the architecture and capabilities of the system and lessons learned from a test implementation at the Arboretum at Flagstaff designed for public outreach.
1 Introduction

Ecologists and environmental scientists need field data. In many research studies, this entails long-term monitoring of coupled environmental processes. These processes include meteorological variables, such as air and soil temperature and photosynthetically active radiation (PAR), as well as other environmental quantities and biotic responses including soil moisture, sap flux and tree trunk diameter. Measurement of most of these has been automated for years using dataloggers of various types. These measurements typically are performed in conjunction with human field work, e.g., sampling seed traps and using portable soil moisture measurement devices.

The dataloggers used have traditionally been of two types, wired and standalone devices. Wired arrays are relatively complex instruments with wired interfaces to multiple external high-precision transducers with a simple programming interface (e.g., dataloggers from Campbell Scientific). In addition to the complexity of installation, wired arrays are invasive and subject to rising costs of the copper-wire interconnections required. Standalone dataloggers (e.g., Onset Computer Hobo or Maxim iButton loggers) can provide similar data collection at greater spatial coverage as they are not constrained by the requirement for interconnections. However, each standalone unit must periodically be found and then connected to a computer or other smart device to upload the data samples. In either case, significant labor is involved in deploying the sensing infrastructure and/or gathering the data.

Many applications require sensing with high spatial resolution over a large coverage area in order to understand spatial variations across scales from meters to kilometers. Since this implies dozens, hundreds, or even thousands of sampling points, wired arrays and standalone dataloggers are inadequate solutions. In the last decade, research in wireless sensor networks has grown tremendously in response to the needs of numerous distributed sensing applications (Pottie and Kaiser 2000; Estrin et al. 2001). Wireless sensors can be viewed as...
sensors with the ability to communicate wirelessly. This capability allows greater density and spatial coverage area while minimizing the labor of data collection and the cost of wired networks. With appropriate algorithms implemented in the wireless sensor’s software, they form a connected network to collaborate in sending the data to a central, terminal node, referred to as the network hub, where it can then be transmitted to the World-Wide-Web (Web) via Ethernet, telephone or satellite links.

Wireless sensor network technology is available or under development for a broad range of applications including manufacturing process and inventory monitoring, control of built environments, monitoring of structural safety (e.g., bridges), public safety and security. We have developed a wireless sensor network called Wireless Sensing And Relay Device Network (WiSARDNet) that specifically targets environmental and ecosystem sensing applications. Previous papers have reported on the technology of the WiSARDNET in situ wireless sensor network (West et al. 2001; Flikkema and West 2002; Flikkema et al. 2002; Flikkema and West 2003; Yang et al. 2005). This paper provides an overview of the design and capability of the complete WiSARDNet Field-to-Desktop cyberinfrastructure, which integrates the in situ wireless sensor network and data-center hardware and software to provide a complete solution for sampling the environment, transferring the information to networked server, and displaying the information via the Web anywhere in the world. Other wireless environmental sensor network experiments are reported in Mainwaring et al. (2002), and Tolle et al. (2005).

2 Requirements

The goal of environmental and ecosystems sensing is to deliver science-quality data to the user; in the case of research, the data should be delivered to a server accessible at the investigator’s laboratory. To accomplish this, a WiSARDNet consists of numerous wireless devices called WiSARDs. A WiSARD that collects data and forwards it along the network is referred to as a WiSARD sensor node. A WISARD that serves as the central, terminating point in the wireless network is called a WiSARD hub. WiSARD sensor nodes also serve as relays
for other sensor nodes farther from the hub, since limited energy and power resources prevent every node from having a reliable wireless link to the hub. The WiSARD hub has the additional capability to transmit the gathered data over a wired, cellular or satellite link. This link terminates at a database server, where the information collected by the WiSARDNet is processed and stored. An application specific website then presents the user with the information in the form of easy to interpret graphs and plots.

A number of requirements drove the WiSARDNet design. First, a deployed WiSARDNet should be minimally invasive to prevent disturbance of the environment, theft, and vandalism. This implies that the sensors should be as small and unobtrusive as possible. Because a wireless sensor node is in simple terms a datalogger with a radio, it consists of three main functional components: transducer interface electronics to gather the data, a radio for communication, and a tiny computer to plan and execute the sensor node’s activities. Each wireless sensor node should interface with a broad spectrum of science-quality transducers, including temperature, PAR, and soil moisture, and also use a rugged, weather-resistant package. All of these characteristics must be achieved at a low cost, monetary and ease of installation and maintenance.

Perhaps the most challenging requirement for a wireless sensor network is long battery life, since battery replenishment is a labor-intensive hence expensive exercise. While this is relatively easy to achieve in standalone dataloggers, the addition of a radio to support wireless networking requires a significant amount of energy. The problem is compounded when small sensor node size is desired (driven by the need to minimize invasiveness), limiting the size and capacity of batteries. In addition, many environments, such as forests with dense canopies, limit the potential of solar power.

When the network is deployed and the WiSARD sensor nodes are powered up, the network configures itself into a data-gathering configuration so that all data flows to the WiSARD hub. To achieve the full potential of wireless capability, the design supports transparent incremental deployment, i.e., the automatic integration of new nodes that are deployed to add coverage or to replace failed WiSARD sensor nodes. This allows the end
user to deploy and maintain the WiSARDNet without having to individually configure each unit. Even within the application domain of environmental/ecosystems sensing, deployments differ significantly. For example, if a particular variable of interest has a low spatial rate of fluctuation (bandwidth), then the relevant data could be captured more efficiently with a deployment of lower spatial density and spatial extent. This implies that the wireless networking technology should be scalable in network coverage, size and density.

These disparate (and often conflicting) requirements have driven the engineering design of the WiSARDNet system, which encompasses the disciplines of analog and digital electronics, radio-frequency electronics, signal processing, communication and networking, embedded computing system design, and mechanical packaging.

We developed the WiSARDNet Field-to-Desktop system to enable the seamless flow of data from sensors to a user’s desktop computer anywhere in the world. It is a complete end-to-end system where the internal workings of the network and data processing are performed automatically to present the user with graphical data displays that are updated in real time (up to networking delays). To do this, additional hardware and software were integrated into the WiSARDNet system.

3 Design

The WiSARDNet sensor nodes employ a modular hardware/software architecture to meet the heterogeneous requirements of sensing, data wireless reception and transmission, and information processing and presentation. To support science-quality sensing, WISARD sensor nodes use a dual-computer board design, with the labor divided between a brain board that provides communication and networking services and a transducer data acquisition board that handles the details of the data acquisition. In the WiSARD hub nodes, the data acquisition board used in WiSARD sensor nodes is replaced by a board that provides communication interfaces, global time acquisition, and non-volatile memory for data archival. Both WiSARD sensor nodes and hubs use a third radio board designed around a wireless transmitter/receiver chip operating in the 900-928 MHz Industrial,
Scientific, and Medical (ISM) radio frequency band. These boards, along with batteries, waterproof strain-relief fittings for transducers, and an antenna port, are integrated into a rugged, weatherproof polycarbonate enclosure (Figure 1).

![WiSARDNET sensor node deployed on a tree trunk. The node is attached to the trunk using easily-obtainable UV-resistant cord. Note the antenna (pointing downward) and the wires from transducers entering the WiSARD enclosure.](image)

Each WiSARD sensor node has a rich array of interfaces to high-accuracy external transducers for measurement of multiple channels of PAR (e.g., LI-COR photodiode-based transducers), temperature (type T thermocouples), and soil moisture (capacitance-based Decagon ECH2O Probes). The nodes also include interfaces to smart peripherals such as the Vaisala WXT-520, which measures rainfall and hail, wind velocity and direction, and relative humidity. We have also developed and implemented the capability to measure sap flux using the Granier method with two type T thermocouples connected in series to measure the difference between heated and unheated probes. The data collected by the WiSARDNet can be archived on the WiSARD hub, waiting for the user to visit the deployment site and transfer the data to a laptop computer. This raw data can be transferred and processed using a computer program to generate processed data files for easy viewing and analysis. The
process requires the user to manage a large number of data streams, one for every transducer on every sensor node. While this is useful from an engineering standpoint, allowing easy access to raw data for debugging and testing purposes, it is not convenient for long-term field studies.

The components of the WiSARDNet Field-To-Desktop system are depicted in Figure 2. The first component is software, called NetBridge, links a WiSARDNet to the Internet and the Web, and runs on any standard desktop computer. This computer, referred to as the WiSARDNet server, is connected to the WiSARD hub via a standard computer data cable. Every data packet from the WiSARD sensor nodes received by the WiSARD hub is sent to the WiSARD server over this cable. The NetBridge software running on the WiSARD server listens for these data packets and records them. Instead of waiting for the user to run the data processing, the software processes the data on the fly, storing the information on the WiSARD server in a relational database. The processing includes formatting and conversion operations and allows for the storage of raw and processed information (e.g., the raw thermocouple reading vs. the calculated temperature). This data can be accessed locally, via standard keyboard and monitor, or it can be accessed remotely through a variety of methods. If the WiSARD server has access to the Internet, the data can be accessed from anywhere in the world. The NetBridge software is highly configurable, including the option to write the data to multiple locations, in case the WiSARD Server has limited storage space, the remote connection to WiSARD server has limited data throughput, or the data should be streamed to multiple destinations.
To facilitate data analysis, a web application was created to extract the data from the database and display it graphically. This web application consists of easy to use web pages that display the data based on user inputs. The user can select which transducers from a WiSARD sensor node to plot; multiple selections are allowed for easy comparison between sensors and nodes. This web application is easily configurable for any database. The application can be run on the WiSARD server at the deployment location or it can be run on a remote server better suited to handle web traffic and multiple users using the application at the same time. Combined with the configurability of NetBridge, this gives the user a high degree of flexibility for any particular deployment, depending on the computer resources available. With the processing and the graphical display software, the user can view graphical plots of the data from any computer with Internet access. These plots can be updated in real time, due to the on-the-fly processing of the incoming data. No special software is needed on the user's computer as all of the processing and display is done on the WiSARD server and web server.

Figure 2 - WiSARDNET Field-to-Desktop flow diagram. The MySQL database server can reside on the same computer hosting the WiSARD Server, the computer hosting the web server, or another any other machine on the Internet. There can also be multiple database and web servers.
NetBridge is a combined communication and data processing system. The software currently runs on Linux operating systems; work is currently being done on a version of the software with the same functionality that will run on Microsoft Windows operating systems. The WiSARD hub connects to the WiSARD server via a standard 9-pin serial port. NetBridge listens for packets incoming on the serial port. When one arrives, the data processing is performed. The information is extracted and inserted into a database. A configuration file specifies the information needed to insert the data into any database accessible via the Internet. This includes the location of the database, local or remote, the user name and password need to access the database and the table in the database where the data will reside. By default, NetBridge always writes a backup copy of the data to the local database server.

If the deployment is located in an area with a local network or reliable Internet connection, then whenever NetBridge receives new data it can simply open up a connection to the remote database and write the data. NetBridge is capable of dealing with unreliable connections to the Internet, which can occur at remote sites. If the WiSARD server fails to connect to the remote database, then the data is stored in a queue. If the connection is successful the next time, NetBridge sends the data and clears the queue. All data remains in the queue until it is successfully transmitted to the remote database(s).

In some deployments the remote connection is intermittent. For example, satellite or cellular mobile phone connections to the Internet are expensive and may be charged on a “talk-time” basis. For these situations, NetBridge can be configured to temporarily store all sensor data in the queue and connect to the remote database at scheduled times, eliminating the need for a constant connection. This configurability was designed so the system is flexible enough to fit the widest possible range of deployment scenarios.

Any standard computer can be configured as a WiSARD Server. The current version of NetBridge software is built to run on the Linux operating system, due to the ease of adapting open-source industry-standard software tools to the required needs of the system. The web server framework that provides the capability to integrate the
web server and database is known as a Linux Apache MySQL PHP (LAMP). A LAMP server consists of an Apache web server, a MySQL database server, and a PHP interpreter all resident on a Linux operating system. These three server applications integrate with each other extremely well, facilitating the development of the web application in PHP. MySQL is the database system used to store the processed data from the WiSARDNet processed by the NetBridge software. MySQL was chosen for its ability to be integrated into many different application platforms, including programs written in most modern computer languages and PHP web applications. The Apache server hosts the web page that the user interfaces with to display the graphs generated by the PHP application.

The web application and display page are compatible with any web server capable of supporting PHP scripts and viewable with any web browser. This allows the web site to be hosted on a different machine from the WiSARD Server (and if needed, in a remote location), in case the WiSARD server isn’t powerful enough to handle the web traffic and the processing software and displaying the web page for multiple users. Additionally, the database server can also be hosted remotely if the WiSARD server cannot handle the database size or high incoming traffic. In summary, the three server applications, Apache, MySQL, and NetBridge, can be run at three different locations, at the same location, or any combination. However, due to the amount of server applications running and communicating with each other, it is very important to make sure that necessary security precautions are in place to prevent unauthorized use of the machine or corruption of the stored data. A security script is provided with the NetBridge software that can be run to secure the servers.

At remote sites, power is often provided by a battery-backed solar array, so the available power to run the WiSARD server and satellite/cellular modem is limited due to cost constraints. Typical personal computers can consume 80 W or more, requiring a large solar array. To control the cost associated with this or other types of remote power sources, we are porting NetBridge to a small (“single-board”) Linux computer that is fanless and uses only solid-state (flash memory) disk for minimum power consumption.
4 Results

The in situ WiSARDNET technology has been deployed to enable a new degree of data quality in ecological and environmental field studies, as well as other environmental monitoring applications. We currently have three separate WiSARDNet deployments operating across the United States. The first consists of three WiSARDNet networks in the Duke Forest of North Carolina that are supporting ecologists’ efforts to characterize the role of fine-scale environmental phenomena in the maintenance of ecosystem diversity in Eastern deciduous forests. The second deployment is mapping the effects of rainfall and soils in the coastal redwoods of California. And in the third deployment, we will determine the effects of scale on eddy covariance measurements of ecosystem energy balance in Northern Arizona. We expect that the results of these studies will have global implications for biological diversity and ecosystem function.

The first WiSARDNet Field to Desktop system was deployed at The Arboretum at Flagstaff as part of a public outreach program in a joint venture with the Arboretum and Northern Arizona University’s Merriam Powell Center for Environmental Research. Figure 3 shows how the Field to Desktop architecture is adapted to this particular deployment. The deployment consists of five WiSARD sensor nodes collecting data on microclimates at the Arboretum site. These 5 sensor nodes connect to a WiSARD hub that streams data to the WiSARD server. The Internet connection at The Arboretum at Flagstaff is reasonably fast, capable of sustained download rates of approximately 400 kilobytes per second. However, the connection is not capable of hosting a web page or database server. Thus, in this deployment, the WiSARD server writes the data to a database server in the Wireless Networks Research Lab located on the Northern Arizona University campus. The University’s connection is capable of handling large amounts of incoming and outgoing traffic, making it idea to host the database.
The web application for the Arboretum is hosted on a server operated by the Merriam Powell Center and is accessible to Arboretum visitors at a touch screen kiosk. The web application also provides information on microclimates, specifically in Northern Arizona, and how wireless sensor networks can help us understand how microclimates effect plant growth and ecosystem dynamics. Additionally, the application is made publically accessible so that any computer with an Internet connection can go to the website and view the same displays and information presented on the kiosk.

5 Discussion

One of the most compelling applications of wireless sensor network technology is dense spatio-temporal sensing of environments to enable better understanding of environmental and ecosystem processes across multiple scales. In the WiSARDNet project, we have completed the development of a prototype wireless environmental sensor network technology and have applied it in several field studies. In this paper, we have outlined the WiSARDNet Field-to-Desktop cyberinfrastructure that is adaptable to diverse applications and
deployments, and have shown how the architecture is implemented in a deployment at the Arboretum and Flagstaff.

In ongoing work to improve the technology, we are currently developing new algorithms for data-gathering networks to further enhance WiSARD sensor node battery lifetime and to improve the network’s performance in inferring data and models for ecosystem processes (Flikkema et al. 2006).

6 Literature Cited


7 Acknowledgements

This work was partially supported by the National Science Foundation under grants BDEI-0131691 and EF-0308498, Northern Arizona University, and Microchip Technology, Inc. We would also like to thank our colleagues, J. Clark, B. Hungate, George Koch, and S. Sillett, as well as the NAU Merriam-Powell Center for Environmental Research, for their on-going collaboration and assistance on this project.