Report for 2005MN98B: Wireless Technologies Applied to Environmental Variables and Nutrient Loadings

Publications

- Conference Proceedings:
  - Jazdzewski, J.D., M. Hondzo and W.A. Arnold, (2006) Stream Water Quality Monitoring using Wireless Embedded Sensor Networks. Future poster presentation at the Minnesota Water 2006 and Annual Water Resources Joint Conference, October 24-25, 2006, Minneapolis, MN.
  - Hondzo, M.; Arnold, W.A.; Novak, P.J.; Hozalski, R.M., 2006. Wireless technologies and embedded networked sensing: application to integrated urban water quality management. Paper presented at the ASCE World Environmental and Water Resources Congress, Omaha, NE, May 21-26, 2006.

Report Follows

Wireless Technologies Applied to Environmental Variables and Nutrient Loadings

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Executive summary

The design and deployment of a real-time wireless sensor network for monitoring stream water quality parameters has been investigated. Multiple networking systems have been studied for efficiency and applicability in the field. These include the Crossbow Technologies Xmesh Mote Sensor Network and the Campbell Scientific PakBus Network. The Campbell Scientific system was selected considering its reliability, advanced software applications, and general ease of use. A laboratory grade nitrate biosensor was adapted for *in situ* field measurements to be used in conjunction with the concurrently developed sensor network. The measurement longevity is only restricted by the limited nitrate biosensor lifetime. A protocol has been developed for maintaining and sustaining the biological component of the sensors here at the University of Minnesota, thus reducing biosensor cost and startup time. The wireless technology will be deployed in the summer of 2006 to establish a real-time sensor network along Minnehaha Creek, Minnesota. With adjustable sampling protocols and sampling intervals of five minutes, the network will monitor turbidity, temperature, water level, and nitrate concentration. The network will provide unparalleled spatial and temporal resolution of the monitored parameters. The acquired data will then be compared to isolated USGS grab samples which are made typically on a biweekly time interval. The network data will provide a basis for quantifying temporal and spatial heterogeneities of nitrate, temperature, turbidity, and discharge in the Minnehaha Creek. Water quality will be observable as a dynamic response to land use gradients and hydrological transients rather than as an equilibrium described by average properties. This approach will enable process-based scaling and forecasting of water quality in streams from the in-stream processes to the watershed level. The wireless network developed in this project is focused on an urban stream, but can be expanded to include other watersheds with different land uses in the future. Generated data and scaling relationships will transform urban planning practices and management of water quality in streams draining urban land.

Introduction

Increasing urbanization across the world has progressively degraded the water quality of streams draining urban land (Booth et al., 2005; Welch et al., 2005a). Streams and rivers draining urbanizing watersheds are ecologically degraded and generally experience a consistent suite of effects named the "urban stream syndrome" (Welch et al., 2005b). General symptoms of the urban stream syndrome include more frequent large flow events with a shorter duration of the storm hydrograph, reduction in channel complexity, elevated concentrations of contaminants and pollutants, reduced retention of natural organic matter (NOM), elevated turbidity, and increased biomass of filamentous algae (Hatt et al., 2004; Meyer et al., 2005). The mechanisms driving the urban stream syndrome are complex and interactive. The complexity of urban land use with associated heterogeneity in physical, chemical, and biological variables presents a research challenge of quantifying the mechanisms by which urban-derived stressors control water quality in streams. To obtain a complete diagnosis of the symptoms of even a single compound within a watershed requires adaptive and frequent event-driven sampling protocols over the range of scales. Wireless sensors and wireless networks are emerging technologies that are designed for concurrent measurements of parameters that experience spatial and temporal variability (Crossbow Technologies; Delin et al., 2004). These technologies are extremely well-suited for quantifying mechanisms between urban-derived stressors and stream water quality.

The deployment of a field-based wireless network for the concurrent measurement of environmental conditions, variables, and contaminants or surrogates for contaminants with adaptive sampling protocols is critical for understanding the input and fate of biological and chemical species throughout a watershed. Many inputs are non-steady state in nature. For example, pesticides enter streams after storm events, particularly at certain times of the year, the outflow of estrogenic compounds from wastewater treatment plants varies with time (*e.g.,* Schoenfuss et al., 2002), and the loading of NOM to a watershed will vary significantly with season and hydrologic events. In conjunction with non-steady state input flows of various species of interest, processes themselves often are either inherently non-linear in nature (the microbial transformation of compounds, for example) or are linear, but dependant on non-linear drivers. An example of the latter is the photo-transformation of pesticides in the environment. Direct photolysis rates are linear with respect to compound concentration and light intensity (Mill, 1999), but light intensity is inherently non-linear over time and space. Indirect photolysis in agricultural and urban streams is even more complicated. This process is a second-order reaction with a dependence on the concentration of hydroxyl radical. The hydroxyl radical concentration, in turn, is dependant on nitrate concentration, alkalinity, light intensity, and light penetration depth (Brezonik and Fulkerson-Brekken, 1998). The non-steady state nature of meteorological and hydrological processes, coupled with biogeochemical processes which are either non-linear processes or linear processes that are dependent on non-linear drivers, result in a system that is fundamentally variable with time and space and inherently far from equilibrium. Such a system requires frequent, tightly-spaced measurements to capture the dynamics of various pollutants entering, flowing through, and reacting or accumulating within the system boundaries.

Methods

Crossbow Mote Work

Software

The first step in this research was the acclimatization of the network operating environment. This included a familiarization with the TinyOS operating system developed at UC Berkeley and the C programming language (Kernighan and Ritchie, 1988). Both frameworks are the primary protocols for the Crossbow sensor network and function in a Linux based system. A 2-Day Wireless Network Training Seminar was attended at Crossbow Technologies in San Jose, CA to learn more about the system structure and how to design and deploy a useful sensor network.

Other available resources were used, such as customer support and user forums in learning the mote network system.

Hardware

The initial networking platform tested was developed by Crossbow Technologies. Prior to attending the workshop, a MICA2 Basic Kit was purchased for testing. A minimal Crossbow sensor network consists of two major parts (Fig. 1 & 2). The first is a remotely located mote/sensor node used for sampling, processing and radio transmission. The second is a server/gateway node used for radio receiving, processing and storage of experimental network data in a database format. An initial test-bed network was built in order to research the applicability of the network. The mote/sensor node was built using a MICA2 mote and a MDA300 generic sensor board.

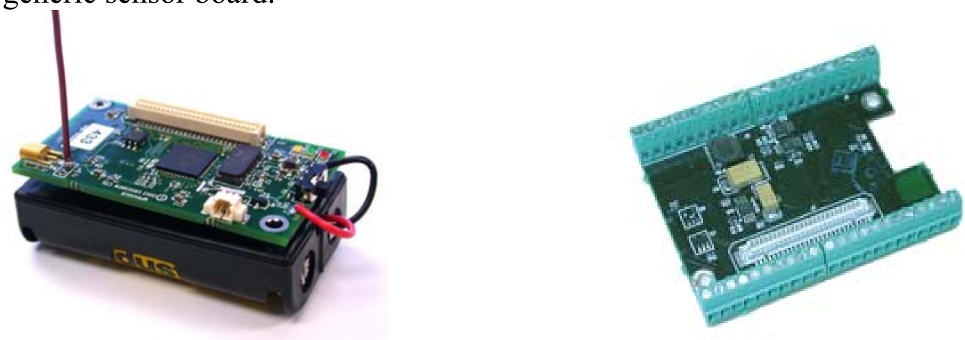

Figure 1: MICA2 mote (left) used for processing and communication; MDA300 sensor board (right) used for generic sensor sampling. This is known as the mote/sensor node. (Not to scale)

Several standard voltages were attached to the sensor board inputs in order to test the operation and applicability of the network as it applies to the transfer of measurement data. Sampling was done at near real-time, first through a gateway board directly connected to a PC. Data was logged in a generic database format on the PC. This was done to become familiar with the operation of the system. Preparations for outdoor deployment were also designed for this system. The transmission range of the motes was tested and they were then outfitted with higher quality antennae and ground plates to increase the transmission range. Designs were also made for power supply systems and housing enclosures. A remote server/gateway node was then built using a Stargate Gateway developed for the Crossbow by Intel, Inc. (Fig. 2). It uses a compact flash memory card for database storage and a PCMCIA wireless card for wireless communication.

Figure 2: Stargate Gateway used to receive network data packets for database storage. This is known as the server/gateway node.

A radio link for transmission of data was setup between the mote/sensor node and the server/gateway node (Fig. 3). A wireless link was setup between a PC and the sever/gateway. Transmission tests were performed to test the acquisition of sensor data at the mote/sensor node as well as radio transfer to the server/gateway node and wireless transfer to the PC.

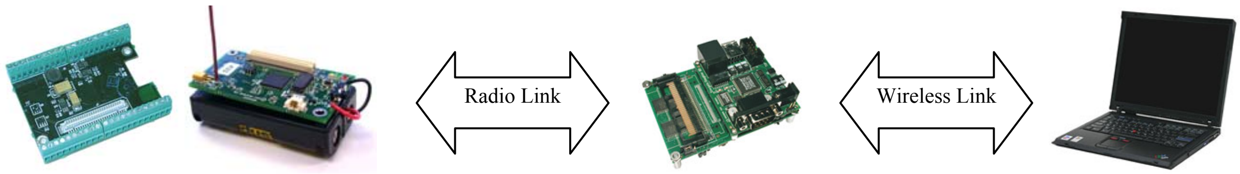

Figure 3: Crossbow test-bed setup used for transfer of data from field to PC. From left to right: sensor/mote, server/gateway and PC.

The Stargate runs a PostgreSQL database on a Linux operating system. It has low power consumption and can be outfitted with a wireless air card, allowing it to be placed in the field and contacted via a cellular network for network database access. Attempts were made to customize the sampling code executed by the mote/sensor node. This would allow the sensor measurements to be customized. Also, the Crossbow developed MoteView software platform was tested for managing the database of measurements stored on the Stargate server.

<u>Campbell Scientific Work</u>

Research into the Campbell PakBus Network was done in order to determine if it was a viable option for the creation of a wireless sensor network. Planning was done for a sensor network consisting of one sampling SubStation and one sampling BaseStation. The SubStation is run by a CR206 datalogger (Fig. 4) which samples four sensors (turbidity, depth, temperature and nitrate concentration).

Figure 4: Campbell Scientific CR206 (left) and CR1000 (right).

This station is in radio contact with the BaseStation, which is run by a CR1000 datalogger and samples the same four types of sensors (Fig. 4). The BaseStation will be in cellular contact with the University of Minnesota, Saint Anthony Falls Laboratory. The setup allows both stations to be accessed from the laboratory at any time. Both stations are solar powered and are entirely self-sufficient.

Locations for data collection in the Minnehaha Creek are currently being considered. The desired site will have the following attributes:

- At or near a USGS grab sample station.

- The network will spatially span a potential nitrate loading point caused by natural organic matter, storm water discharge or fertilizer run-off.
- The stations will be isolated from hard wired power to test its solar capabilities.
- The stations will be isolated from internet technology to test its data transfer capabilities.

<u>Unisense Nitrate Biosensors</u>

Many options are available for measuring nitrate at high levels, using ion reactive membranes. However, in order to measure nitrate at the typically low levels associated with river monitoring, alternative methods need to be employed. In collaboration with Unisense, Denmark, we have adopted a sensor designed for measuring nitrate concentrations in the laboratory and modified the sensor for field application (Fig. 5). The biosensor has a 90% response time of 90 sec and a minimum detection limit of 2 µg/L as N. Detecting nitrate concentrations at low concentrations is a unique feature of this sensor. The NO_3^- ion enters the sensor by molecular diffusion through an ion-permeable membrane. Active denitrifying bacteria in the sensor reduce NO_3^- to N_2O, which is detected by an N_2O transducer. The current through the electrode is converted into a voltage by means of a picoammeter. The voltage is proportional to the concentration of nitrate present in the water sample. The nitrate-sensitive biochamber is replaceable and has a lifetime of about 2 months.

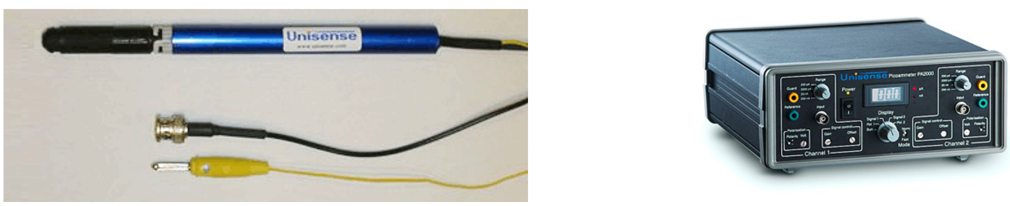

Figure 5: Nitrate biosensor (left) and measurement picoammeter (right).

Results to date

<u>Crossbow Mote Work</u>

A test-bed system was constructed and radio communication was established between the sensor/mote and server/gateway. Code was written to allow wireless communication with the server/gateway and a wireless connection to the server/gateway was made with a PC. However, connections and data transfers were very unreliable. Consequently, one of the major downfalls of the Crossbow system was found to be the complexity of its architecture and the lack of research friendly software. While connections were made, there were problems transferring data into the database from the sensor/mote as well as accessing the database for data retrieval from the PC. While some attempts to customize the sampling code were successful, the complexity of the programming framework was an important limitation of the setup. The system was unstable and difficult to work with. For example, due to lack of a hardware clock on the motes, the time stamping of measurements would need to be done computationally using a timer. This would lead to temporal sample inaccuracies throughout the network and also would make synchronization of the networking system virtually impossible. Temporal accuracy of a measurement system is of utmost importance and the Crossbow system does not address these issues. Continuation with the system would have required a vast amount of background work in the area of computer programming and a fair amount of custom program code. Due to project constraints this was not a viable option. The decision was then made to begin researching the possibility of using another system to form the network.

Campbell Scientific Work

All of the appropriate sensor equipment needed to form a field sensor network has been ordered and received. Power tests have been run to ensure that the solar powered charging system will be able to maintain the network. A collective sensor housing unit has been designed using the four sensors (Fig. 6). The unit will be attached to a fence post in the Minnehaha creek and the sensor height can be easily adjusted using a hose clamp. The sensors will be attached to the station via a conduit to an onshore tripod which supports an enclosure, solar panel and a radio and/or cellular antenna. Contained within the enclosures are the datalogger, radio/cell phone, picoammeter and batteries.

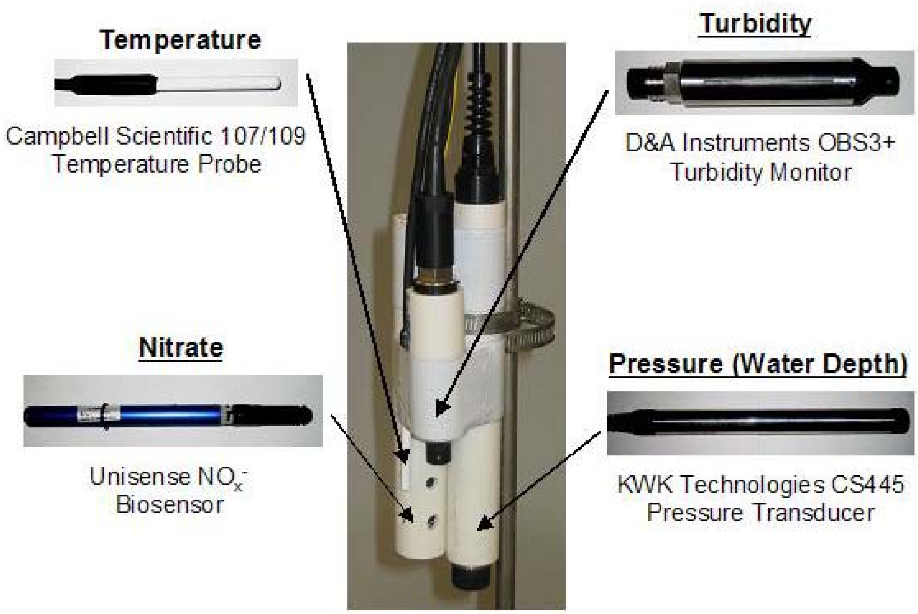

Figure 6: Sensor housing unit used with each station (UofMN design).

Programs have been written for both dataloggers that take one sample per minute for five minutes, and then record the average in a database. These programs can be easily edited to alter the temporal resolution of the network. They are also easily edited to perform any number of statistical or computational operations on the data itself. Programming algorithms have been developed to control power supply to the sensors, powering them only when necessary for a measurement. An optimization of power usage is a very important requirement for wireless networks which are powered by solar radiation. Radio communication has been established between the base and sub stations for two way data transfer. Programs and commands can be sent to either station and data can be downloaded from the stations. The variables running in the program can also be monitored in real-time. Once deployed, the stations need periodic visits for routine physical maintenance or the occasional troubleshooting. The stations are currently being bench tested in the Saint Anthony Falls Laboratory and deployment is scheduled for the middle of June.

Unisense Nitrate Biosensors

A culture of the denitrifying bacteria used in the biosensors was acquired from Unisense. The bacteria were successfully inoculated, cultured and placed in cold storage. As a result, sterile chambers may now be purchased from Unisense at a considerably lower cost and the inoculation of the biochambers can be performed at the University of Minnesota. This will also eliminate the biosensor inactivation time that is commonly associated with the shipment of pre-inoculated chambers. The sampling code for the dataloggers also includes a procedure to measure the voltage put out by the biosensor picoammeter. The code samples and processes the voltage into a nitrate concentration based on a user entered linear calibration unique to each biosensor. Then the nitrate concentration is stored in the database along with the other sensor measurements.

Summary of findings

- Crossbow Technologies has developed a very compact and power efficient XMesh Mote Network system that offers many possibilities for scientific data acquisition. The system does not provide adequate communication software support needed for practical applicability in aquatic environments. Major deficiencies with the technology include:
    - time stamping of measurements at the time of acquisition;
    - sampling program versatility allowing the researcher to easily customize the sampling technique; and
    - inefficient database management.

  For these reasons, the Crossbow XMesh Mote Network was not chosen for developing a stream monitoring wireless sensor network.

- The Campbell Scientific PakBus Network was found to be much better suited for the task of creating a sensor network. User-friendly communication software enables quick and reliable integration of a variety of sensors in the network. A two station network has been developed and is ready for deployment in the Minnehaha Creek. The network will monitor turbidity, depth, temperature, and nitrate concentration at two different locations with adjustable sampling intervals (from minutes to hours) along the Minnehaha Creek. The network can later be easily expanded to more stations to increase spatial resolution.

- A design protocol for the integration of the Unisense laboratory biological nitrate sensor into the sensor network has been completed, thereby allowing the sensor to be placed in an *in situ* measurement environment.

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Useful websites

Campbell Scientific Inc., 2006. (http://www.campbellsci.com/index.cfm)

Crossbow Technology – Wireless Sensor Networks, 2006. (http://www.xbow.com/wireless_home.aspx)

TinyOS Community Forum, 2006. (http://www.tinyos.net/)

Unisense A/S, 2006. (http://www.unisense.com/)

List of publications & presentations resulting from this project

Jazdzewski, J.D., M. Hondzo and W.A. Arnold, (2006) *Stream Water Quality Monitoring using Wireless Embedded Sensor Networks.* Future poster presentation at the Minnesota Water 2006 and Annual Water Resources Joint Conference, October 24-25, 2006, Minneapolis, MN.

Hondzo, M.; Arnold, W.A.; Novak, P.J.; Hozalski, R.M., 2006. Wireless technologies and embedded networked sensing: application to integrated urban water quality management. Paper presented at the ASCE World Environmental and Water Resources Congress, Omaha, NE, May 21-26, 2006.

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Award: NSF-IGERT (Graduate education grant)
Principal Investigators: C. Neuhauser (PI), R. Hozalski, M. Hondzo, S. Sugita, C. Paola, W. Arnold N. Jindal, S. Shekhar
Title: IGERT: Non-equilibrium dynamics across space and time: a common approach for engineers, earth scientists, and ecologists
Amount: $2,819,194
Period of Support: 08/01/05-07/31/10.

Award: NSF
Principal Investigators: M. Hondzo (PI), W. Arnold, R. Hozalski, N. Jindal, and P. Novak
Title: Wireless technologies and embedded networked sensing: Application to integrated urban water quality management
Amount: $250,440
Period of Support: 08/01/06-07/31/08.

Description of student training provided by project:
Name: Jeremiah D. Jazdzewski
Program: Department of Civil Engineering, University of Minnesota
Degree being sought: Masters of Science