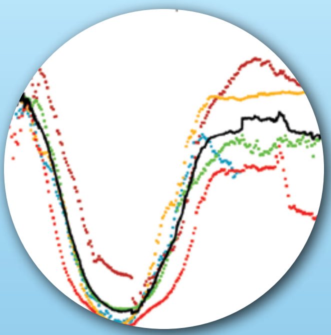
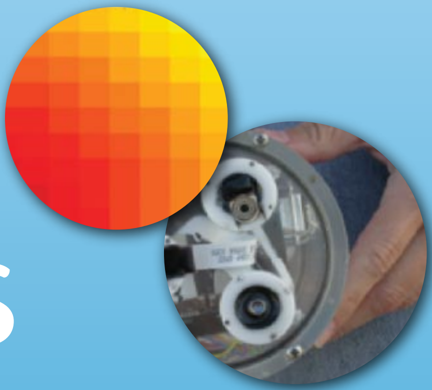


Broadband, Low-Cost, Coastal Sensor Nets



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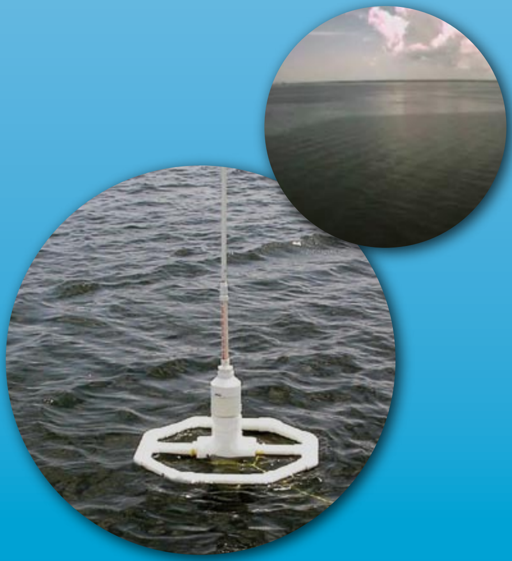

High-bandwidth wireless communication links could provide major improvements to integrated ocean observatory systems. The potential of broadband wireless networks opens up numerous application scenarios for coastal environmental monitoring, research, and security. High-bandwidth networks allow the incorporation of bandwidth-hogging video/voice applications along with arrays of environmental sensors, which typically have low data rates. We remotely monitored an ecological hotspot in Tampa Bay waters using low-cost sensor nodes deployed in a wide-area, broadband sensor network. The sensors used in this network were an example of micromachining technology called micro-electro-mechanical-systems (MEMS). Sensors using this technological approach can be designed to monitor the biological, chemical, and physical environment, or they can be used to detect microbial, chemical, or radiological agents. One key device in our demonstration was a low-cost, low-power salinity sensor (CTD) made of waterproof, printed circuit MEMS materials. Another element of the sensor Web was an offshore camera that permitted remote viewing of surface-water conditions in real time for a sustained period. The sensors were attached to an array of easily fieldable 802.11b-capable network nodes. The low cost of the sensor nodes makes it possible to economically deploy a large array. These high- and low-bit-rate sensor nodes provide real-time data and are remotely configurable, enabling an adaptive broadband observing system.

INTRODUCTION

Human migration, industrial development, and urbanization along marine and inland coasts, and an increase in shipping and maritime traffic, have led to an accumulation of environmental stressors within coastal regions. These stressors, which challenge the management and sustenance of coastal regions, include population pressures, climate change, fisheries depletion, habitat alterations, freshwater diversion, pollution, contaminants, harmful algae blooms, invasive species, extreme storms, and other coastal hazards. The scope of these threats ranges from local to global in both occurrence and scale, and the effects may be widespread and long lasting.

Understanding the ways stressors move through the environment is key to supporting a sustainable coast. However, without environmental monitoring and assessment, we cannot judge how well we are reducing our impact and managing the coastal-water resource. Ocean sensing systems and networks are an emerging reality, but the pace of growth has been hindered by their expense (Glenn and Schofield, 2003). The immediate problem for ocean sensor network growth is not lack of technologies, but lack of means to deploy numerous measurement devices inexpensively. In addition to reduced sensor cost, low-cost, high-bandwidth wireless communication links are needed to provide major improvements to integrated ocean observatory systems. In particular, high-bandwidth networks allow incorporation of bandwidth-hogging video/voice applications in combination with arrays of low-data-rate environmental sensors. The availability of video-over-network and data-over-network will be more properly matched with the needs of coastal ecosystem monitoring efforts. The enabling potentials of broadband wireless networks and inexpensive sensors open up numerous application scenarios for coastal environmental monitoring, research, and security sensing networks.

COASTAL SENSOR NETWORK PROJECT

This project was an effort to create a low-cost, rapidly deployable coastal sensor network. The sensors and the sensor net had to address the primary issues of cost and high-level integration. The strategy for nodes and network was to combine inexpensive materials and managed 802.11b-based communications with MEMS technology for the CTD sensors. The completed sensor net, demonstrated in local Tampa Bay waters as a proof-of-concept, addressed the project criteria.

> The wireless network described here enables distributed sensor networks to be used in emerging ecosystem observatories that require high-density sensor deployment and video.

Network Description

The wireless network used modified 802.11b technology operating in the 2.4 GHz ISM (industrial, scientific, medical) band. Dual radio access point/routers were preferred, which allowed the system higher throughput and ease of deployment over multiple single-radio access points. Using standard communication protocols has the advantage of compatibility with any TCP/IP network infrastructure, which is increasingly available in coastal regions. This approach also makes it easy to integrate the sensor network with more holistic initiatives that have recently been developed toward cyberinfrastructure for integrated coastal monitoring.

We first successfully demonstrated this technology strategy on a large scale in Tampa Bay, combining all elements of a real-world system. Since the initial deployment, we have further improved the platform for longer and more automated observations. In this scenario, six buoys containing wireless modules and our PCBMEMS CTD were deployed within a two-mile radius around a Coast Guard tower equipped with a dual-radio, battery-operated, wireless local area network (WLAN) station. High-gain antennas on the telemetry modules and a sector antenna on the tower allowed connection of the buoys at this significant distance. A second radio was attached to a directional antenna and a 1-watt amplifier, completing a seven-mile link across the bay to a base station with a similarly equipped radio. Due to the 802.11b protocol's high level of compatibility with the existing infrastructure,

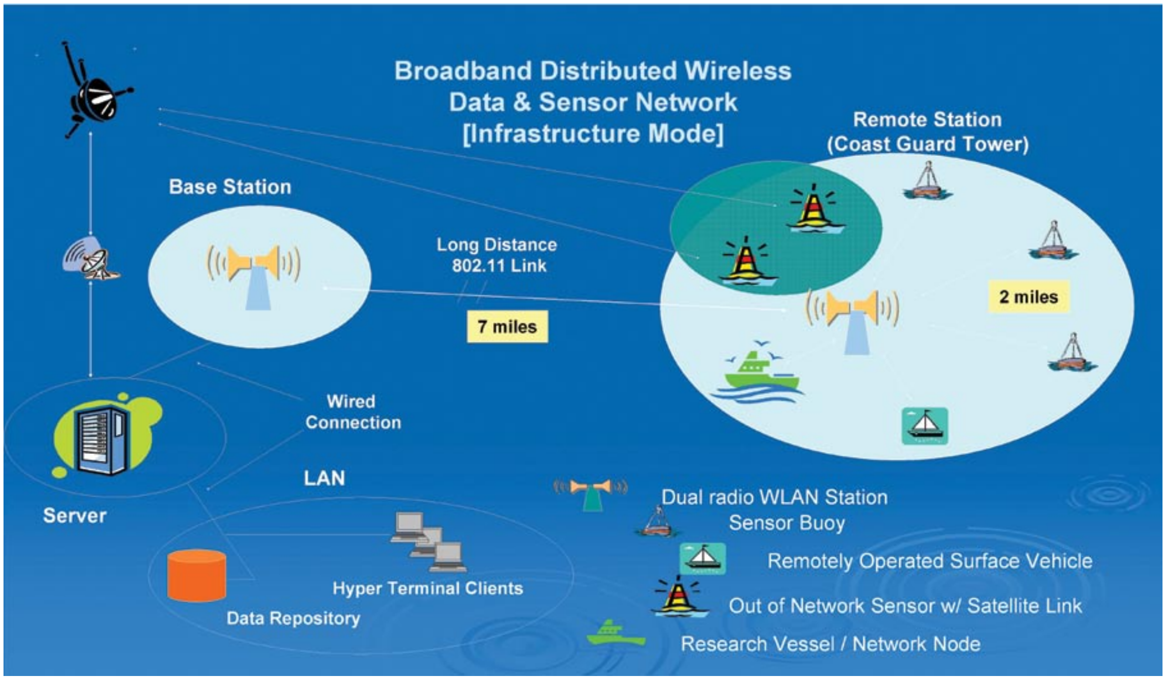

Figure 1. Environmental sensor network array in Tampa Bay. A point-to-point, and point-to-multipoint, topology is used to extend the broadband wireless sensor network. The network can accommodate both low- and high-bit-rate sensors simultaneously.

a server simply handled the wired connection to HyperTerminal clients, which then dumped data into a repository. Figure 1 shows the configuration of our test-bed topology.

Because the telemetry units were assembled with standard equipment, the research vessel deploying the network could connect to the buoy platforms, to all of the Internet resources available at the base station, and to LAN services ashore via the tower. This communications system also connected to out-of-network sensors linked by satellite back to the server on the shore side. Overall, this network deployment was planned, executed, and removed in a matter of three days, demonstrating operational high-bandwidth availability in the coastal environment of 802.11b at 2.4 GHz.

Low-Bandwidth Sensor

Ocean conductivity, temperature, and depth (CTD) data are important parameters for oceanographic research applications. Conductivity and temperature, commonly used in the monitoring and analysis of marine and freshwater environments (Woody et al., 2001), are fundamental properties of marine and fresh waters from which salinity and density can be derived. We developed a low-cost, printed-circuit-board-based (PCB), expendable salinity sensor that uses immersion electrode-based conductivity detection and a resistive temperature device on the same PCB substrate, along with a discrete silicon piezoresistive pressure sensor.

The Liquid Crystalline Polymer (LCP) salinity analysis system (Broadbent et al., 2007) was constructed using novel PCBMEMS fabrication techniques. The salinity system consists of three microsensors: a four-electrode thin-film conductivity cell, a thin-film resistive temperature sensor, and a piezoresistive pressure sensor. We used an LCP as the microsensor substrate due to its low-moisture permeability properties, thus making it capable of withstanding direct immersion in the harsh marine environment. Once assembled, the entire salinity-analysis system is 10 cm x 10 cm in size (Figure 2). The conductivity, temperature, and pressure microsensors constitute a total salinity-analysis system with integrated open path fluidics and electronic functions, manufactured in an economical PCBMEMS format. The sensor system has RS-232 output and is configured for placement with the miniature buoy platform.

Figure 2. A low-cost, printed circuit-board-based salinity sensor system. Top: The conductivity and temperature sensors along with a silicon micro-electro-mechanical-systems (MEMS) pressure sensor mounted on an underwater housing end cap. Bottom: An assembled prototype of the conductivity, temperature, and pressure sensors for underwater measurements (acrylic vessel dimensions: ~ 10 cm diameter x 10 cm length).

Figure 3. Buoy/node of the environmental sensor network in Tampa Bay. The system, designed to be portable and low cost, is made of lightweight PVC. The cylindrical core that extends under water contains the batteries. The omnidirectional antenna projects upward. The orbital rings provide the buoy with floatation.

Figure 4. Wireless camera node providing images of the surrounding environmental sensor network area in Tampa Bay. The remote images can be used to assess surface water activity and weather conditions.

Network Node

We constructed the buoy using inexpensive, durable, flexible, and lightweight PVC. The buoy has a cylindrical core that extends underwater and contains all of the heavy materials (batteries), giving it a low center of gravity. Orbital rings provide the buoy with flotation and a stable handling and attachment point (Figure 3). The buoy is topped off with a high-gain 2.4-GHz antenna in a PVC enclosure. This configuration allows any sensor with an RS-232 interface to be connected to the platform. The buoys were located within a two-mile radius of the remote tower transmitter. This distance limitation can be overcome by using the telemetry modules with a mesh-networking approach that can be integrated into the firmware with a simple software upgrade.

High-Bandwidth Sensor

The coastal sensor net incorporated a video camera with built-in CPU (Trendnet) to assess the region being sampled by the CTD array. An embedded Web server made the camera a standalone, TCP/IP-addressable viewing system. The camera, once fitted to the 802.11b telemetry module, could be accessed, controlled, and managed remotely from shore over the Internet via a Web browser. The camera was a low-cost, 640 x 480 pixel, color CMOS (complementary metal oxide semiconductor) sensor with automatic gain control. The camera could focus from 20 cm to infinity. JPEG image compression was incorporated, and the frame rate was

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20 per second. Images were stored on a server array at the shore facility.

We were able to remotely control the camera system, and to view water conditions, which were periodically assessed and correlated with data generated from the CTD array. The system was able to monitor sea surface states, weather conditions, boating/human activity, and surface flotsam and jetsam in the wide area. The last factor was particularly useful because the three-day deployment occurred during a historically significant *Karenia Brevis* (red tide) bloom and fish kill, so the ability to view and record water movement was most useful.

Enhancing the Network-Managed Power

The choice of 802.11b over other network protocols and proprietary solutions came at a cost of higher power consumption. Due to the lack of a low-power receive mode, any inactivity on the link directly translates to unwarranted use of battery capacity. Transmission at low data rates also means inefficient use of available battery capacity. To overcome both of these problems, we implemented variable sensor-sampling rates, data logging, and variable transmission schedules. In this configuration, the sensor samples the environmental variables at a certain rate and a data logger accumulates the data. The telemetry unit is powered up only during certain periods of the day, commanded by the transmission schedule. At that time, all of the data in the logger is dumped at high speed in a short amount of time. With the main emphasis on slower-changing biological and chemical events, the data did not need to be available in real time; rather, a four-hour transmission interval was satisfactory. This near-real-time availability provides a good balance between power usage and event tracking. During the transmission portion of the scheduling, a researcher can reconfigure the sampling and transmission rate, allowing for adaptive sampling within the sensor net for better feature tracking while extending the battery power available.

SENSOR NETWORK DEPLOYMENT

Deployment of the sensor nodes for this distributed environmental sensor network was governed by the algorithms (Vincent et al., 1998) and the availability of large-scale oceanographic models of Tampa Bay tidal flow (Vincent et al., 2000; Sanderson et al., 2006). These low-resolution models of flow, salinity, temperature, and depth provided the basis for deployment of sampling algorithms in order to estimate these variables. The sensor node location design was based on parametric modeling of salinity gradients at different depths and phases of the tidal cycles. The region of Tampa Bay selected for the distributed environmental sensor network deployment encompasses an area of approximately 4 km^2.

SENSOR NET DATA ANALYSIS—PROOF OF CONCEPT

Experiments were conducted from approximately 11:00 a.m., July 7, 2005, to 11:00 a.m., July 10, 2005. All five sensors were functional for more than 95% of the experimental period. There were several intervals where reliable data were lost for short periods. Commercially available CTDs (three Micro CTDs from Applied Microsystems Ltd.) were deployed as part of the network to validate and benchmark the data and to provide additional nodes.

Figure 5 displays basic salinity data for the five sensors. The cyclic pattern of these data is consistent with the tidal flow patterns predicted by the oceanographic models of Tampa Bay. These models

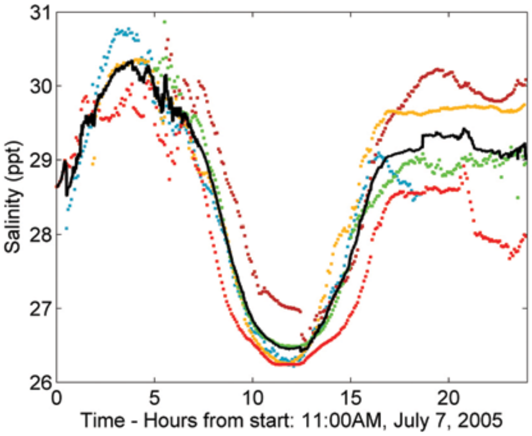

Figure 5. Salinity data from the five CTD sensors. The sensors correspond to line colors as follows: 102 = Blue; 103 = Brown; 104 = Amber; 105 = Green; 106 = Red. The black line shows the average of active sensors at each time.

characterize the peak flood and ebb times corresponding to the flow patterns. The distributed sensor array provides information on the spatial gradients and how they change with time. These spatial gradients are estimated by parametric interpolation of the measurements in space and time and are displayed at intervals in the sequence of images in Figure 6. Each image displays a region approximately 3 x 3 km. The sequence shows the trend of average salinity change and the superimposed spatial salinity gradient (from lower left to upper right, southwest to northeast, of each image). This combination of spatial and temporal patterns demonstrates the unique capability of this type of real-time sensor sampling and analysis to provide insight into oceanographic processes.

CONCLUSIONS

The wireless network described here enables distributed sensor networks to be used in emerging ecosystem observatories that require high-density sensor deployment and video. Despite the wide availability of serial instrumentation, many marine applications, such as real-time imaging, require high bandwidth. These applications usually employ proprietary solutions that require huge investments in equipment and charge subscription services based on monthly fees or data-usage patterns. Some of these solutions rely on satellite or cellular communications. Using an 802.11b approach allows access to the inherent high-bandwidth capabilities of the protocol, which has become increasingly available as wireless infrastructure expands in marinas, seaside hotels, ports, waterfront properties, and municipal networks. This high-bandwidth availability will enable further applications in underwater optical and acoustic video for ecosystem observation and coastal/port security, as well as low-bitrate sensors for coastal observations.

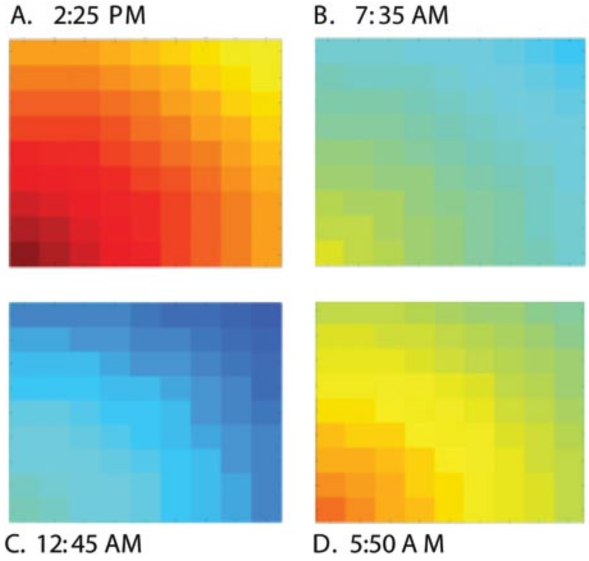
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Figure 6. Spatial gradients of salinity in a region approximately 3 x 3 km, corresponding to the sensor array locations deployed during the exercise in Tampa Bay. Red is high salinity, and blue is low salinity.

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