A High-Speed, Wireless Network for Ship-to-Ship and Ship-to-Shore Data Exchange

NATHAN D. POTTER AND TIMOTHY J. COWLES

College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

(Manuscript received 22 January 1999, in final form 19 October 1999)

ABSTRACT

Wireless networking equipment was installed on three research vessels and at three shore stations during the 1998 Thin Layers Experiment in East Sound, Washington. This wireless network provided high-speed data communication between scientists on separate vessels and permitted rapid transfer of data from vessels and from moored instruments to a common file server at one of the shore stations. This server was connected, via wireless link, to a local Internet service provider, thus permitting continuous Internet access from each vessel and each shore station. The wireless network used 900-MHz and 2.4-GHz spread spectrum systems and provided throughput comparable to T1 lines. Omnidirectional antennas were used between vessels and shore stations, providing communications at ranges up to 12 km. Such systems provide the capability for rapid data exchange during coordinated field operations and give investigators on separate vessels the opportunity to adapt sampling protocols to rapidly evolving conditions observed a few kilometers away.

1. Introduction

As the oceanographic community has developed and adopted the use of high-resolution in situ instrumentation to characterize rapidly evolving biological phenomena (e.g., Cowles et al. 1998), we have also developed the need for high-speed, high-bandwidth data communications. We must communicate between vessels and moored instrument packages, between research vessels, and between research vessels and shore sites used for data collection and processing. When conducting multiple vessel operations it is often important for different vessels to modify sampling strategies in response to changes in oceanographic conditions. These changes are usually detected with instruments that are ‘‘data-rich’’ (e.g., Barth et al. 1998; Hanson and Donaghay 1998). Verbal descriptions of these complex datasets via radio telephone or simplified graphics sent via facsimile (fax) often fail to communicate all of the pertinent information to the recipient. High-speed wireless communications technology can allow researchers on separate vessels, or on shore, to exchange these large complex datasets in near real time.

In the summer of 1998, a multiinvestigator, multidisciplinary experiment [Thin Layers (sponsored by the Office of Naval Research)] was conducted in East Sound, Orcas Island, Washington, to investigate the formation and maintenance of planktonic layers in the water column. The experiment included a moored array of profiling conductivity–temperature–depth probes (CTDs) and optical sensors, multifrequency acoustical sensors, moored acoustic Doppler current profilers (ADCPs), shore-based meteorological stations, and overlapping intervals of high-resolution vertical profiling of the water column from three different vessels. The relatively confined geometry of the field location (Fig. 1), combined with the dynamic sampling requirements of the experiment, suggested that data communication/data sharing could be enhanced with a wireless network between vessels, shore stations, and moored instrumentation. In this paper we describe our installation of wireless networking equipment on three research vessels and at three shore stations to facilitate that data exchange and to improve our ability to respond to changing conditions across the domain of the experiment.

Our wireless networking equipment operated successfully for the duration of the 13-week field program. During the 1-month intensive phase of this experiment (June 1998), scientists on board any of the three research vessels, or at the shore sites, had a local network connection that operated at greater than T1 speeds [1.54 megabits per second (Mbps), see Table 1]. In addition, this local network was connected to the Internet Wide Area Network (WAN) via a shared T1 line provided by a local Internet service provider (ISP). Users of this system had the functionality of a typical scientific net-

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Corresponding author address: Nathan D. Potter, College of Oceanic and Atmospheric Sciences, Oregon State University, Oceanography Administration Bldg. 104, Corvallis, OR 97331-5503.
E-mail: ndp@oce.orst.edu

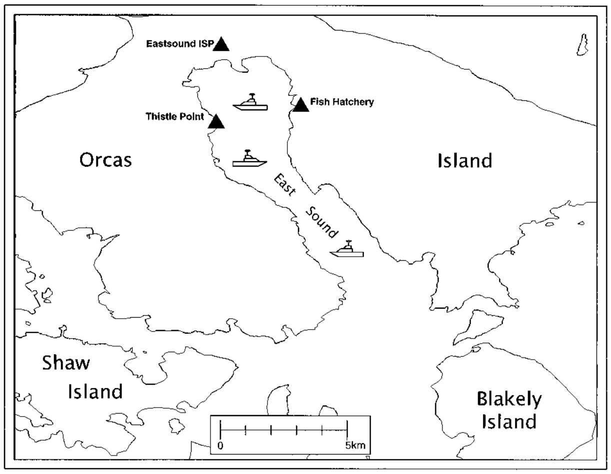

FIG. 1. Map of the study area in the San Juan Islands, Washington. The locations of the wireless networking shore and vessel stations are indicated in and around East Sound on Orcas Island.

TABLE 1. Comparison of communication speeds for various wired and wireless systems.

Communication carrier	Maximum speeds
Standard phone line[a]	56 Kbps
ISDN[b]	128 Kbps
T1[c]	1.544 Mbps
ADSL[d]	6.0 Mbps downlink|640 Kbps uplink
Cable modem[e]	30 Mbps downlink|3.0 Mbps uplink
Cell phone[f]	9.6 Kbps
INMARSAT B[g]	64 Kbps
DSSS (SpeedLAN Plus)[h]	2.0 Mbps
DSSS (SpeedLAN 10)[i]	10 Mbps

[a] Modulation on POTS lines limited to 53 kHz by FCC.
[b] Ford and Lew (1997).
[c] Ford and Lew (1997).
[d] Ford and Lew (1997).
[e] DOCSIS (1998).
[f] CDMA Development Group (1998).
[g] INMARSAT Inc. (1998).
[h] Wave Wireless Networking Inc.
[i] Wave Wireless Networking Inc.

work environment. Scientists connecting to the network required only the hardware or software normally used to connect a system to a 10Base-T or Thin-Net network with 10-Mbps bandwidth.

In the sections that follow, we provide technical background on the wireless equipment used, a comparison between wired and wireless communications, and an evaluation of system performance over a 12-km range in the study area.

2. System description

Since each shore–shore or ship–shore wireless connection requires a clear line-of-sight (LOS) between antennas, installation of systems is constrained by local topography and requires a site specific design solution. In addition to local topography, vegetation, man-made features (buildings, parking lots, towers), and existing radio signal traffic on desired transmission frequencies are all elements to consider in system design. We avoided serious technical difficulties in constructing a reliable wireless network through careful evaluation of local conditions and then designed the system to accommodate these conditions.

We conducted two site surveys (Winter, Spring 1998) before installing wireless shore stations in late May 1998. These surveys, conducted by car, on foot, and by boat, were essential for locating shore sites that met the following criteria:

- clear LOS to the proposed location of the moored instrument array,
- maximal ‘‘viewing’’ area (LOS) of the waters of East Sound (Fig. 1),
- clear LOS to the local ISP in the village of East Sound, and
- antenna locations at least 50 ft above the water surface (for optimal transmission/reception).

The Thistle Point location (Fig. 1) met the above criteria, and we were able to rent a small cottage at this site that served as the base station for the wireless network for the duration of the experiment.

In addition, we conducted radio frequency spectrum analyses during the site surveys to determine ambient noise levels (i.e., other radio traffic) across the frequency bands used by the various wireless systems under evaluation (primarily 915 MHz and 2.4 GHz). We found little or no ambient noise in the 2.4-GHz band, but found some strong transmission signals at 930 MHz. This was within 2 MHz of the upper bound of the 915-MHz band of our planned wireless system, and we were concerned that our transceiver's common mode rejection might not reduce this 930-MHz signal to acceptable levels. The potential interference from the 930-MHz signal (due to local cellular phones and pagers) during the summer months dictated our selection of 2.4-GHz wireless systems for the critical communication linkages (ship–ship, ship–shore) of the field program. Additional frequency spectrum analyses conducted at the time of installation (late May 1998) indicated no change in the ambient 930-MHz signal levels, so we used the 915-MHz systems for the shore–ISP connection (see following sections).

We narrowed our selection of various commercially available wireless units based on several criteria:

- ease of configuration changes between 915 MHz and 2.4 GHz for installed units,
- expected signal strength (range) over the sampling domain,
- cost, and
- service/support.

On the basis of these criteria, we chose the SpeedLAN Plus™ wireless bridge/router, a direct sequence spread spectrum (DSSS) (Schreier 1996) system from Wave Wireless Networking (Sarasota, Florida), as the back-

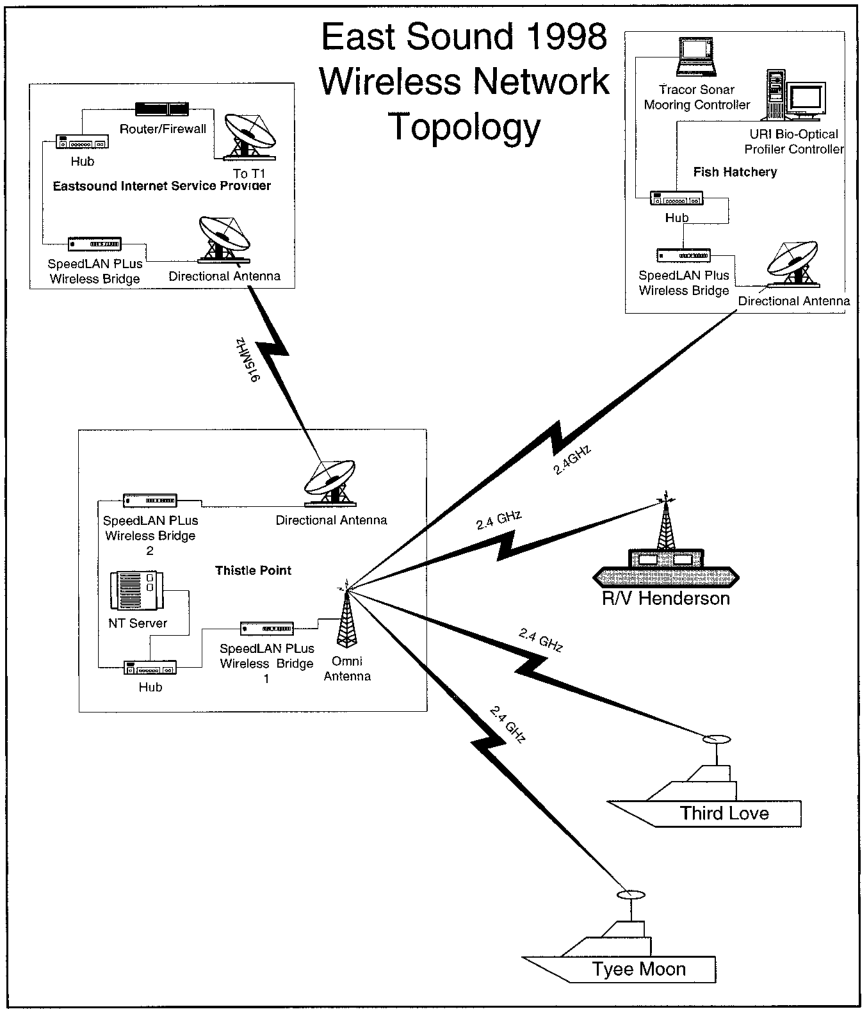

FIG. 2. Schematic diagram of the network infrastructure. Note the two wireless bridge/routers at the Thistle Point base station (hub of star network topology), one (2.4 GHz) for connections with the Fish Hatchery shore station and the vessels, the other (915 MHz) for connection to the East Sound ISP.

bone of our wireless network. This system provided a flexible platform for building a robust network. The SpeedLAN Plus acts as a Media Access Control layer learning bridge (Ford and Lew 1997) and has a rudimentary set of routing capabilities. It has a (theoretical) maximum data transfer rate of 2 Mbps. This transfer rate exceeds that of a dedicated T1 line. The SpeedLAN systems also can be configured to support a number of different network designs, topologies, and transmission frequencies. Because of the shoreline topography of East Sound (Fig. 1), and the autonomy that the different participants had in conducting their respective science operations, we chose to build a star topology network with the SpeedLAN systems in base station mode (Fig. 2). This allowed boats to come and go from the area of wireless coverage without the need of any special action by a system administrator. Other possible configurations would have required one or more of the wireless systems to be rebooted by a technician every time a roaming vessel entered or departed the area of wireless coverage. These alternate configurations provide more efficient use of the transmission medium by multiple transmitters but are intended for use in establishing links between fixed sites rather than between roaming vessels.

The wireless network was designed in conjunction with land- and ship-based wired networks, and the network was optimized for speed and traffic isolation using a combination of wired and wireless links (Fig. 2). Our goal was to isolate local scientific network traffic from incoming/outgoing traffic between the Thistle Point server and clients on the Internet WAN. This was partially achieved by the use of the bridging functions of the SpeedLAN systems located at Thistle Point. However, to achieve complete isolation we needed to use a different transmission frequency for the wireless link between Thistle Point and the ISP than the frequency used to support our scientific operations. We could have accomplished this in either of the following ways.

1) By using two channels in the 2.4-GHz band. (The SpeedLAN systems use a 20-MHz-wide band for their transmissions. Since the 2.4-GHz band assigned by the Federal Communications Commission (FCC) for this kind of application is 75 MHz, the SpeedLAN systems were designed to allow for the use of six channels. Adjacent channels overlap each other, so in actuality there are really three distinct usable channels in the 2.4-GHz band.)
2) By using a 915-MHz system for one link and a 2.4-GHz system for the other.

We chose the latter because we wanted to see if the 915-MHz system would work in the presence of the strong local signal that we detected at 930 MHz. A 915-MHz system was used for the wireless link from Thistle Point to the ISP, and all of the wireless systems critical for ongoing science used 2.4-GHz systems. This ensured that if for some reason there was a problem with the 915-MHz band the scientific work would not be adversely affected. The 915-MHz systems at Thistle Point and at the ISP used high gain directional antennas for their communications. An omnidirectional antenna was used in conjunction with the 2.4-GHz system at Thistle Point, and this system was configured as a polling base station and served as the hub of the star network topology, while all other systems (on vessels or at shore sites) were configured as satellite stations. In addition to the two SpeedLAN wireless systems, the base station network at Thistle Point had an NT server and several other ancillary computer systems that were engaged in data processing, software development and testing, and network analysis. Each of the three research vessels (R/V *Henderson,* R/V *Tyee Moon,* R/V *Third Love*) had 2.4-GHz wireless systems with omnidirectional antennas mounted about 50 ft above the water to optimize signal transmission. [Our initial design goal was clear signal transmission/reception over a 4-km range. Calculation of the necessary first Fresnel zone clearance (McLarnon 1997, unpublished manuscript) for this signal range indicated an antenna height of approximately 50 ft]. Antennas mounted on the vessels were placed above the other structures on the vessel in order to obtain clear LOS in any direction. We configured each vessel with a local wired network that supported both 10Base-T and Thin-Net connections. The R/V *Henderson* had the largest local network with approximately 16 systems online. The other two vessels had local networks with one or two computers connected. At our Fish Hatchery shore station, we had a single 2.4-GHz wireless system providing network connectivity to the computers controlling a subsurface array of moored instrumentation. This 2.4-GHz system used a directional antenna for wireless connection with the Thistle Point base station. Each of the wireless systems that were dependent on shore-based electrical power were placed on an uninterruptible power supply, as was the system on the R/V *Henderson.*

3. Comparison between wireless and wired communications

It is important to make the distinction between bit rate (bits per second), baud rate, and byte rate (bytes per second) when discussing the capabilities of various methods of transmitting information between computer systems. Measurements of network speed are typically made in the units of bits per second (bps). Bit rate, however, is not synonymous with baud rate (Ford and Lew 1997; Tannenbaum 1989). The bit rate is the actual throughput rate for bits, whereas the baud rate is the modulation rate on the physical medium. High-speed network systems are usually described in terms of kilobits per second (Kbps) or megabits per second (Mbps). Actual data transfers over a particular connection, however, are typically measured in units of bytes per second (Bps), with higher-speed transfer rates discussed in kilobytes per second (KBps). Data transfer rates indicate how quickly a certain amount of data can be moved between two systems. This measurement carries, concealed within it, all of the overhead of a particular transfer method [such as kermit, network file system (nfs), or file transfer protocol (ftp)]. For example, for every 8-bit byte of data that is transferred, 8–18 (or more) bits may have been transmitted across the connection to achieve the transfer. This overhead makes up the major portion of the discrepancies observed between theoretical and actual measurements of throughput and transfer rates.

In recent years, the typical speed for telephone modems has improved to 33 Kbps (Table 1). New technologies, such as Integrated Services Digital Network (ISDN), cable modems, and Asymmetric Digital Subscriber Line (ADSL) offer significant performance increases. Of these only the cable modem and ADSL offer throughput that equals or exceeds the throughput obtained by the wireless DSSS system used in the study. However, most of these new technologies are available only in areas of high population density, and thus may not be available at field study sites. Other wireless technologies, such as data transmission via cell phone or the International Mobile Satellite Organizations (INMARSAT) offer limited throughput (Table 1). New cell phone technologies such as cdmaOne version three may offer speeds as high as 1.5 Mbps where service is available (CDMA Development Group 1998; QUALCOMM Inc. 1998). Chayes et al. (1998) have developed a wireless network system called SeaNet for ship–shore communications in the global oceanic environment using the INMARSAT B system. They achieved actual data tranfer rates between 1.65 and 4.49 KBps with the SeaNet system.

We avoided incremental charges for increased throughput capabilities (as in subscription-based sys-

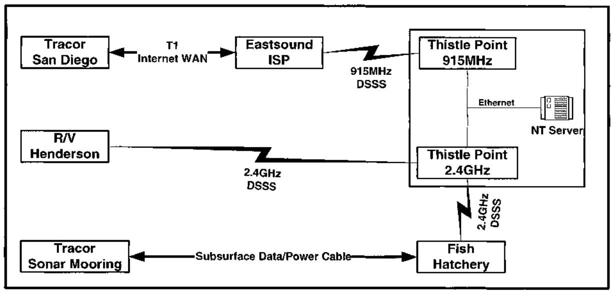

FIG. 3. Schematic diagram of the data paths from moored instruments, vessels, and shore stations.

tems) by purchasing both ends of the wireless connection. The cost to set up this type of wireless network involves the initial investment in hardware (~$5000–$7000 per site, depending on antenna choice and installation details), system maintenance including regular software and hardware upgrades, and Internet WAN connectivity. During the East Sound 98 project our Internet WAN connection and a block of 128 IP addresses cost $550 per month.

4. Benefits of wireless communications during the field experiment

Once the system was constructed, we were able to use the network as if we were in a regular network environment. Scientists on the research vessels were able to collect data and then archive it to our server at the Thistle Point base station. In addition, scientists on each vessel could transfer files to computers on other vessels with ease. For example, a group of scientists from TRACOR Systems (San Diego, California), led by Dr. Van Holliday, had a small multifrequency acoustic system for detection and characterization of zooplankton populations (Holliday et al. 1998). This system was deployed on a profiler operated by Dr. P. Donaghay on the R/V *Tyee Moon*. Members of Dr. Donaghay's group made vertical profiles throughout the sound with this system, then transferred the resulting data files to the NT server at Thistle Point. Those files could then be accessed immediately by Dr. Holliday's group for processing and analysis.

Dr. Holliday's team made extensive use of the wireless system. They deployed three subsurface, upward-looking, multifrequency acoustic systems mounted on moorings in the study. These moorings were linked by subsurface cables to a data acquisition and control computer at the Fish Hatchery shore station (Fig. 3); this computer was linked via the wireless network to the TRACOR computers on board the R/V *Henderson*. This allowed the TRACOR group real-time access to their mooring data. The acoustic moorings were kept in place until early August 1998, even though the R/V *Henderson* left the study area on 26 June. With no personnel at the study site after 26 June the TRACOR team used the wireless network to archive data on the NT server at Thistle Point. The files on the server were available to the TRACOR team from their San Diego laboratory, via the network connection to the Internet WAN at the East Sound ISP. TRACOR personnel therefore were able to monitor the state of their moorings, observe their data immediately after collection, and move data files to their home laboratory.

Scientists from our group at Oregon State University (OSU) aboard the R/V *Henderson* used the base station NT server as an archive site for our high-resolution vertical profile data. At the end of each shift on the R/V *Henderson*, all data collected during the shift was backed up on local machines, then transferred via the wireless link to the NT server at Thistle Point. Once on the server, computers at Thistle Point and at OSU (in Corvallis, Oregon) were used to process the data and generate plots. These processed results were accessible, via wireless connections, over the World Wide Web within a few hours of data collection.

The most basic advantage of having our field site wireless network connected via the wireless link to the ISP to the Internet WAN was that all of the scientists enjoyed standard internet connectivity. Scientists working offsite, whether they were in Rhode Island, Oregon, or California had access to the most recently acquired raw datasets. The time interval between acquisition and remote (offsite) access was as little as 30 s. Researchers on the vessels and shore stations in East Sound could move data, check e-mail, access the Web, and otherwise work as if they were at their respective offices at their home institutions. This proved invaluable for ordering replacement parts for broken equipment and for maintaining contact with project investigators unable to participate in the entire field study. When scientific instruments were not working correctly, the scientists could be in direct contact with the instrument manufacturer via e-mail to diagnose the problem. Software updates and bug fixes were also available from instrument manufacturers via the World Wide Web.

5. Observed system performance

We monitored the performance of the wireless system by recording signal strength and signal-to-noise ratios (SNRs) for each end of a wireless link, as logged by the SpeedLAN systems. We developed software that used the Simple Network Management Protocol to extract these data from the SpeedLAN Plus's internal management information base. We merged these data on signal strength (relative units) and SNR with a data stream from a global positioning system receiver to construct maps of our wireless network performance and coverage over the East Sound study area (Fig. 4). We found we could maintain a good connection with excellent throughput for data transfers between the research vessels and the Thistle Point base station as long as we had a clear LOS. We were able to maintain good

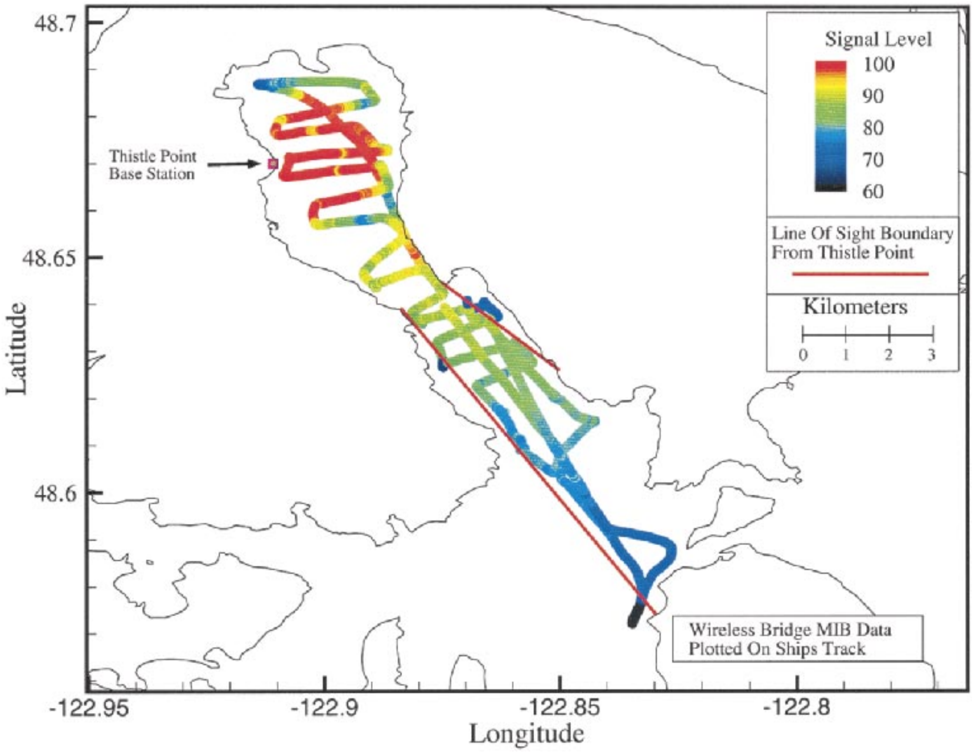

FIG. 4. Map of SpeedLAN signal strength (units 0–100) obtained from field surveys with the R/V *Tyee Moon.*

connectivity and throughput along the entire LOS range from Thistle Point to Blakely Island, a distance of 13 km (Fig. 4). We were able to transfer files to OSU servers consistently at speeds of 30 KBps or more, and frequently as fast as 102 KBps. It should be noted that these transfers from the research vessels had to pass through two wireless links prior to arriving at the T1 connection at the East Sound ISP, and then had to traverse the Internet WAN to OSU. Transfer rates from the vessels directly to the NT server at Thistle Point were even faster, with speeds as high as 176 KBps observed in the field. Our transfer rates to the OSU servers were 10–30 times faster than those reported by Chayes et al. (1998) for SeaNet over INMARSAT B. It should be noted, however, that the SeaNet system was designed as a solution for global oceanic communications and that it utilizes an existing communications satellite infrastructure, while our system was designed for relatively close range operations where line of sight can be maintained between nodes.

TABLE 2. Signal strength vs transfer rate in laboratory tests (mean ± 1 std dev).

Transfer rate (kilobytes per second)	Signal strength (relative units)
118 ± 13	57.9 ± 0.3
139 ± 12	76.8 ± 1.1
176 ± 8	79.3 ± 0.6
177 ± 6	89.3 ± 1.1
178 ± 4	100.0 ± 0.0

We conducted additional laboratory tests to quantify the effects of fluctuations in signal strength on data transfer rates. We established a wireless link across the laboratory between two SpeedLAN systems, a ‘‘base station’’ connected to an NT server, and a ‘‘satellite’’ station connected to a PC. The two omnidirectional antennas were incrementally shielded from each other to degrade the transmission and reception of the systems. Transfer rates were measured while using a ftp program. A group of 12 binary files, each about 775 kilobytes in size, were transferred repeatedly from the PC connected to the satellite station to the NT server connected to the base station (Table 2). By combining these laboratory test data with our measurements of signal strength from the East Sound field experiment, we can estimate transfer rates as a function of range from the base station (Fig. 5).

During the field experiment we found a dip in signal strength between 1500 and 3000 m (Figs. 4 and 5). This signal strength dip at 1500 m is likely due to a ‘‘bad bounce’’ of the signal off the water surface that produced a phase shift in the signal that interfered with the directly transmitted component of the signal. We did not investigate this in the field since this local degradation in signal strength at that range did not degrade transfer rates to any noticeable extent. (It proved impractical to simulate this apparent ‘‘multipath’’ problem in the lab-

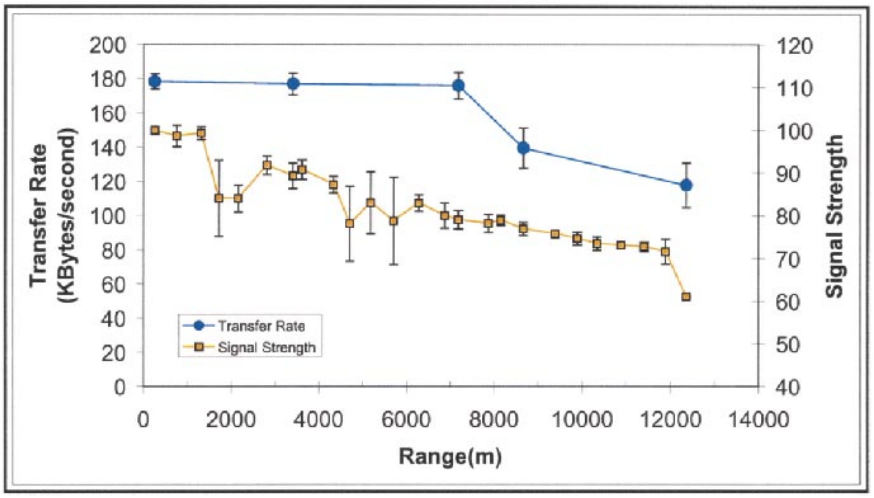

FIG. 5. Relationship between signal strength and range obtained from the field surveys shown in Fig. 4. In addition, the laboratory-derived data transfer rates as a function of signal strength (Table 2) are plotted as a function of range. Note that high data transfer rates are obtained even under conditions of reduced signal strength (see text for details).

oratory, so we can provide only a reasonable speculation about the observed performance within this 1500–3000-m portion of the range.) Other laboratory tests confirmed that signal strengths greater than 80 consistently resulted in transfer rates of about 175 KBps, equivalent to the maximum rates observed during our field experiment. The laboratory tests revealed a sharp drop in transfer rate between signal strengths of 79 and 77 (Table 2), which would correspond to a decrease in transfer rates at ranges between 7000 and 9000 m (Fig. 4). We interpret this drop in transfer rate to result from retransmission of an increasing number of data packets. Such retransmissions of packets consume system resources and slow data transfers. Even with this decrease, however, data transfer rates never fell below 30 KBps, faster than a dedicated ISDN line (Table 1).

The topography of our study area (Fig. 1) made it possible to implement a wireless system that possessed an estimated range of 8–16 km. In general, the effective range of a wireless communications system is limited by the system's ability to differentiate signal from noise in the operational frequency band. If the source signal levels are high enough, then background noise has little bearing on reception and processing of the signal. As the signal strength decreases with respect to the ambient noise it becomes increasingly difficult for a system to discern the signal. Spread spectrum transceivers possess excellent noise rejection characteristics, and thus can be operated at significantly lower output power than conventional transceivers (Schreier 1996; McLarnon 1997). Signal strength at a particular receiver is a function of transmitter power, antenna design, range (distance from the transmitter), and local topography (trees, heavy rain or fog, buildings, hills, etc.). Ambient noise has numerous sources including other systems operating in the same (or adjacent) frequency bands, inclement weather with associated electrical phenomena, sun spot activity, and noise generated from unrelated human activity (motor vehicle electrical systems, avionics, radar, radio, cell phones, etc.) to name a few. Use of DSSS wireless systems in coastal oceanographic applications is primarily limited by physical range between transceivers and line of sight issues. This range limitation may be reduced if wireless power limits (under FCC control) increase over the next few years. In addition, new systems of low earth orbit satellite communications systems are scheduled to come online in the next few years (Griffith et al. 1996). These systems may offer yet another alternative communication path for ship–ship and ship–shore communications.

6. Conclusions

Our high-speed wireless network implementation facilitated daily operations during our multiinvestigator, multivessel field experiment, and contributed to the successful completion of the project. We were able to move data smoothly and rapidly between research vessels and shore stations, provide colleagues with data interpretations on timescales appropriate for making adjustments in sampling strategies, and facilitate data collection and analysis via remote connections. Such high-speed wireless networks are appropriate solutions for many experimental systems in marine, freshwater, or terrestrial habitats that require connectivity at remote locations.

Acknowledgments. We are indebted to Mr. John Hibbs of Solutions Group and the staff of WaveWireless Networking, Inc. for their technical assistance during the design phase of this project. Mr. Christopher Wingard was instrumental in the deployment and maintenance of the system, and logged many long hours of assistance. This project was funded by the Office of Naval Research Grant N00014-97-10349.

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