Shallow Water Acoustic Networks

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ABSTRACT

Underwater acoustic networks are generally formed by acoustically connected ocean bottom sensor nodes, autonomous underwater vehicles (AUVs), and surface stations that serve as gateways and provide radio communication links to on-shore stations. The quality of service of such networks is limited by the low bandwidth of acoustic transmission channels, high latency resulting from the slow propagation of sound, and elevated noise levels in some environments. The long-term goal in the design of underwater acoustic networks is to provide for a self-configuring network of distributed nodes with network links that automatically adapt to the environment through selection of the optimum system parameters. This article considers several aspects in the design of shallow water acoustic networks that maximize throughput and reliability while minimizing power consumption.

INTRODUCTION

In the last two decades, underwater acoustic communications technology has experienced significant progress. Communication systems with increased bit rate and reliability now enable real-time point-to-point links between underwater nodes such as ocean bottom sensors and autonomous underwater vehicles (AUVs). Current research is focused on combining various point-to-point links within a network structure to meet the emerging demand for applications such as environmental data collection, offshore exploration, pollution monitoring, and military surveillance [1].

The traditional approach for ocean-bottom or ocean-column monitoring is to deploy oceanographic sensors, record the data, and recover the instruments. This approach has several disadvantages:

- The recorded data cannot be recovered until the end of the mission, which can be several months.
- There is no interactive communication between the underwater instruments and the onshore user. Therefore, it is not possible to reconfigure the system as interesting events occur.
- If a failure occurs before recovery, data acquisition may stop or all the data may be lost.

The ideal solution for real-time monitoring of selected ocean areas for long periods of time is to connect various instruments through wireless links within a network structure. Basic underwater acoustic networks are formed by establishing bidirectional acoustic communication between nodes such as autonomous underwater vehicles (AUVs) and fixed sensors. The network is then connected to a surface station, which can further be connected to terrestrial networks, such as the Internet, through an RF link. Onshore users can extract real-time data from multiple distant underwater instruments. After evaluating the obtained data, they can send control messages to individual instruments. Since data is not stored in the underwater instruments, data loss is prevented as long as isolated node failures can be circumvented by reconfiguring the network.

A major constraint of underwater acoustic (UWA) networks is the limited energy supply. Whereas the batteries of a wireless modem can easily be replaced on land-based systems, the replacement of an underwater modem battery involves ship time and the retrieval of the modem from the ocean bottom, which is costly and time-consuming. Therefore, transmission energy is precious in underwater applications. Network protocols should conserve energy by reducing the number of retransmissions, powering down between transactions, and minimizing the energy required per transmission.

Some underwater applications require the network to be deployed quickly without substantial planning, such as in rescue and recovery missions. Therefore, the network should be able to determine the node locations and configure itself automatically to provide an efficient data communication environment. Also, if the channel conditions change or some of the nodes fail during the mission, the network should be capable of reconfiguring itself dynamically to continue its operation.

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UNDERWATER ACOUSTIC COMMUNICATIONS

Unlike digital communications through radio channels where data are transmitted by means of electromagnetic waves, acoustic waves are primarily used in underwater channels. The propagation speed of acoustic waves in UWA channels is five orders of magnitude less than that of radio waves. This low propagation speed increases the latency of a packet network. If high latency is overlooked in the design of network protocols for UWA applications, it can reduce the throughput of a network considerably.

The available bandwidth of a UWA channel depends critically on transmission loss, which increases with both range and frequency, and severely limits the available bandwidth [2, 3]. Within this limited bandwidth, the acoustic signals are subject to time-varying multipath [2], which may result in severe intersymbol interference (ISI) and large Doppler shifts and spreads, relative to radio channels, especially in shallow water channels. Multipath propagation and Doppler effects degrade acoustic signals and limit data throughput. Special processing techniques are needed to combat these channel impairments.

Until the beginning of the last decade, due to the challenging characteristics of UWA channels, modem development was focused on employing noncoherent frequency shift keying (FSK) signals for achieving reliable communication. Although noncoherent FSK systems are effective in UWA channels, their low bandwidth efficiency makes them inappropriate for high-data-rate applications such as multiuser networks. The need for high-throughput long-range systems has resulted in a focus toward coherent modulation techniques. Today, with the availability of powerful digital signal processing devices, we are able to employ fully coherent phase shift keying (PSK) modulation in underwater communications. A summary of acoustic modems is listed in Table 1. Interested readers are referred to [3] for detailed explanations of each modem.

As the data rate and range of the systems increase, the complexity of the algorithms grows beyond the capacity of current digital signal processing (DSP) hardware. Current research is focused on DSP algorithms with decreased complexity and multiuser modems that can operate in a network environment.

Type	Year	Data rate (b/s)	Bandwidth (kHz)	Range (km)
Noncoherent	1984	1200	5	3.0S
Noncoherent	1991	1250	10	2.0D
Noncoherent	1997	2400–600	5	10.0D–5.0S
Coherent	1989	500,000	125	0.06D
Coherent	1993	600–300	0.3–1	89S–203D
Coherent	1994	20	20	0.9S
Coherent	1998	1670–6700	2–10	4.0S–2.0S

■ **Table 1.** *A summary of performance metrics for some UWA modems presented in the literature [3]. S indicates a shallow water result, while D indicates a deep water result, generally a vertical channel.*

UNDERWATER ACOUSTIC NETWORKS

Two types of applications have guided the evolution of underwater networks. One is gathering of environmental data, and the other is surveillance of an underwater area. Typically, the network consists of several types of sensors, some of which are mounted on fixed moorings, while the others are mounted on freely moving vehicles. This type of network is called an Autonomous Ocean Sampling Network (AOSN) [4], where the word *sampling* implies collecting the samples of oceanographic parameters such as temperature, salinity, and underwater currents. For surveillance applications, the network consists of a larger number of sensors, typically bottom-mounted or on slowly crawling robots, that can be quickly deployed, and whose task is to map a shallow water area. An example of such a network, called Seaweb, will be described in more detail later.

NETWORK TOPOLOGIES

There are three basic topologies that can be used to interconnect network nodes: centralized, distributed, and multihop topology [5]. In a centralized network, the communication between nodes takes place through a central station, which is sometimes called the *hub* of the network. The network is connected to a backbone at this central station. This configuration is suitable for deep water networks, where a surface buoy with both an acoustic and an RF modem acts as the hub and controls the communication to and from ocean bottom instruments. A major disadvantage of this configuration is the presence of a single failure point [5]. If the hub fails, the entire network shuts down. Also, due to the limited range of a single modem, the network cannot cover large areas.

The next two topologies belong to peer-to-peer networks. A fully connected peer-to-peer topology provides point-to-point links between every node of the network. Such a topology eliminates the need for routing. However, the output power needed for communicating with widely separated nodes is excessive. Also, a node that is trying to send packets to a far-end node can overpower and interfere with communication between neighboring nodes, which is called the *near-far* problem [5].

Multihop peer-to-peer networks are formed by establishing communication links only between neighboring nodes. Messages are transferred from source to destination by hopping packets from node to node. Routing of the messages is handled by intelligent algorithms that can adapt to changing conditions. Multihop networks can cover relatively larger areas since the range of the network is determined by the number of nodes rather than the modem range.

One of the UWA network design goals is to minimize the energy consumption while providing reliable connectivity between the nodes in the network and the backbone. The network topology is an important parameter that determines the energy consumption. In [6], the authors show that the strategy that minimizes energy consumption is multihop peer-to-peer topology. The price paid for the decrease in energy consumption is the need for a sophisticated communication pro-

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tocol and an increase in packet delay. Therefore, special attention should be given to applications that are sensitive to delays.

MULTIPLE ACCESS METHODS

In many information networks, including UWA networks, communication is bursty, and the amount of time that a user spends transmitting over the channel is usually smaller than the amount of time it stays idle. Thus, network users should share the available frequency and time in an efficient manner by means of a multiple access method. Frequency-division multiple access (FDMA), divides the available frequency band into subbands and assigns each subband to an individual user. Due to the severe bandwidth limitations and vulnerability of narrowband systems to fading, FDMA systems do not provide an efficient solution for UWA applications.

Instead of dividing the frequency band, time-division multiple access (TDMA) divides a time interval, called a *frame*, into time slots. Collision of packets from adjacent time slots are prevented by including guard times that are proportional to the propagation delay present in the channel. TDMA systems require very precise synchronization for proper utilization of the time slots. High latency present in UWA channels requires long guard times that limits the efficiency of TDMA. Also, establishing a common timing reference is a difficult task.

Code-division multiple access (CDMA) allows multiple users to transmit simultaneously over the entire frequency band. Signals from different users are distinguished by means of pseudo-noise (PN) codes that are used for spreading the user messages. The large bandwidth of CDMA channels not only provides resistance to frequency selective fading, but may also take advantage of the time diversity present in the UWA channel by employing rake filters at the receiver in the case of direct sequence CDMA [7]. Spread spectrum signals can be used for resolving collisions at the receiver by using multiuser detectors. In this way, the number of retransmissions and energy requirements of the system are reduced. This property both reduces battery consumption and increases the throughput of the network. Hence, CDMA appears to be the most suitable multiple access technique for shallow water acoustic networks.

ROUTING ALGORITHMS

There are two basic methods used for routing packets through an information network: *virtual circuit routing*, where all the packets of a transaction follow the same path through the network, and *datagram* routing, where packets are allowed to pass through different paths. Networks using virtual circuits decide on the path of the communication at the beginning of the transaction. In datagram switching, each node that is involved in the transaction makes a routing decision, which is to determine the next hop of the packet.

Many of the routing methods are based on the *shortest path* algorithm. In this method, each link in the network is assigned a cost which is a function of the physical distance and the level of congestion. The routing algorithm tries to find the shortest path (i.e., the path with lowest cost) from a source node to a destination node. In a distributed implementation each node determines the cost of sending a data packet to its neighbors and shares this information with the other nodes of the network. In this way, every node maintains a database that reflects the cost of possible routes.

For routing, let us consider the most general problem where network nodes are allowed to move. This situation can be viewed as an underwater network with both fixed ocean-bottom sensors and AUVs. The instruments temporarily form a network without the aid of any preexisting infrastructure.

In *ad hoc* networks the main problem is to obtain the most recent state of each individual link in the network to decide on the best route for a packet. However, if the communication medium is highly variable as in the shallow water acoustic channel, the number of routing updates can be very high. Current research on routing focuses on reducing the overhead added by routing messages while at the same time finding the best path, which are two conflicting requirements. Also, the effect of long propagation delays and channel asymmetries caused by power control are issues that need to be addressed when designing network routing protocols to UWA channels.

MEDIA ACCESS CONTROL PROTOCOLS

There are various media access control (MAC) protocols that can be employed to avoid information loss in UWA networks due to packet collisions. We shall focus on the MACA protocol and a variation of this protocol.

The MACA protocol, proposed by Karn [8] uses two signaling packets called Request-to-Send (RTS) and Clear-to-Send (CTS). When A wants to send a message to B, it first issues an RTS command. If B receives the RTS, it sends back a CTS command. As soon as A receives CTS, it begins transmission of the data packet. The nodes can probe the channel during the RTS-CTS exchange [8]. The channel state information can be used to set the physical layer parameters, such as output power and modulation type. These properties of the MACA protocol are essential for efficient UWA network design. It provides information for reliable communication with minimum energy consumption and has the ability to avoid collisions before they occur. The RTS-CTS exchange adds overhead, but the reduction of retransmissions can compensate for this increase.

The MACA protocol ensures the reliability of the end-to-end link with the network layer. If some packets of a message are lost due to errors, the final destination node will ask the originating source to retransmit the lost packets. On highly reliable links, this approach increases throughput, since it eliminates the need to send individual acknowledgments for each hop. In case of poor-quality communication channels, a message will most probably contain erroneous packets. Recovering the errors in the data packet at the network layer will require excessive delay. Generally, error correction is better performed at the data link layer for channels of low reliability, such as radio or shallow water acoustic channels.

The performance and reliability of the MACA protocol may be improved by creating error-free, reliable point-to-point links with the data link control (DLC) layer. For this purpose, Bharghavan proposed the MACAW protocol [9], where an acknowledgment (ACK) packet is transmitted after each successful transaction. Including an extra packet in the transaction increases the overhead, which decreases the throughput. However, it is shown in [9] that, for radio channels, the gain in throughput exceeds the increase in overhead. This result may also apply to UWA channels. The MACAW protocol ignores power control and asymmetries that can occur. Its performance under power control needs to be investigated. Also, the effect of adding more overhead to the protocol in an environment where propagation delays are excessive needs to be addressed.

AUTOMATIC REPEAT REQUEST METHODS

Automatic repeat request (ARQ) is used to detect errors in the data link control layer and then to request the retransmission of erroneous packets. The simplest ARQ scheme that can be directly employed in a half-duplex UWA channel is the stop-and-wait ARQ, where the source of the packet waits for an ACK from the destination node for the confirmation of error-free packet transmission. Since the channel is not utilized during the round-trip propagation time, this ARQ scheme has low throughput. In go-back-N and selective repeat ARQ schemes, nodes transmit packets and receive ACKs at the same time, and therefore require full duplex links. Dividing the limited bandwidth of the UWA channels into two channels for full duplex operation can significantly reduce the data rate of the physical layer. However, the effect on the overall network throughput needs to be investigated.

The selective repeat ARQ scheme can be modified to work on half duplex UWA channels. Instead of acknowledging each packet individually at reception time, the receiver will wait for N packet durations and send an ACK packet with the id number of packets received without errors. Accordingly, the source of the packets will send N packets and wait for the ACK. Then the source will send another group of N packets that contains the unacknowledged packets and new packets.

Acknowledgments can be handled in two possible ways. In the first approach, which is called *positive acknowledgment*, upon reception of an error-free packet, the destination node will send an ACK packet to the source node. If the source does not receive an ACK packet before a preset timeout duration, it will retransmit the data packet. In the case of a negative acknowledgment, the destination sends a packet if it receives a corrupted packet or does not receive a scheduled data packet. A *negative acknowledgment* may help to conserve energy by eliminating the need to send explicit ACK packets and retransmission of data packets in case of a lost ACK packet. When combined with a MACA type MAC protocol, the negative acknowledgment scheme may provide highly reliable point-to-point links due to the information obtained during RTS-CTS exchange.

DESIGN EXAMPLE: SEAWEB

A realization of underwater acoustic networking is the U.S. Navy's experimental Telesonar and Seaweb Program [10]. Telesonar links interconnect distributed underwater nodes (Fig. 1), potentially integrating them as a unified resource and extending naval "net-centric" operations into the underwater battlespace. Seaweb provides a command, control, communications, and navigation infrastructure for coordinating autonomous nodes to accomplish given missions in arbitrary ocean environments. More generally, Seaweb networking is applicable for oceanographic telemetry, underwater vehicle control, and other uses of underwater wireless digital communications.

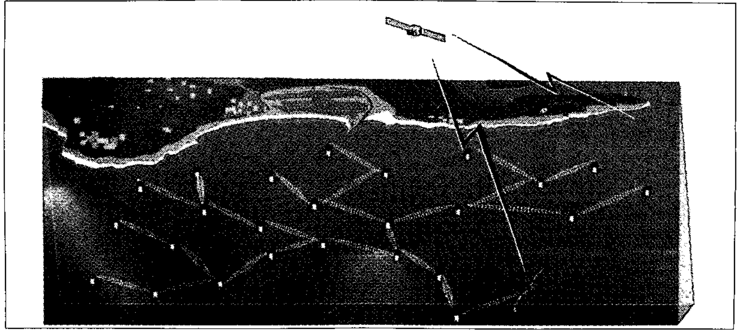


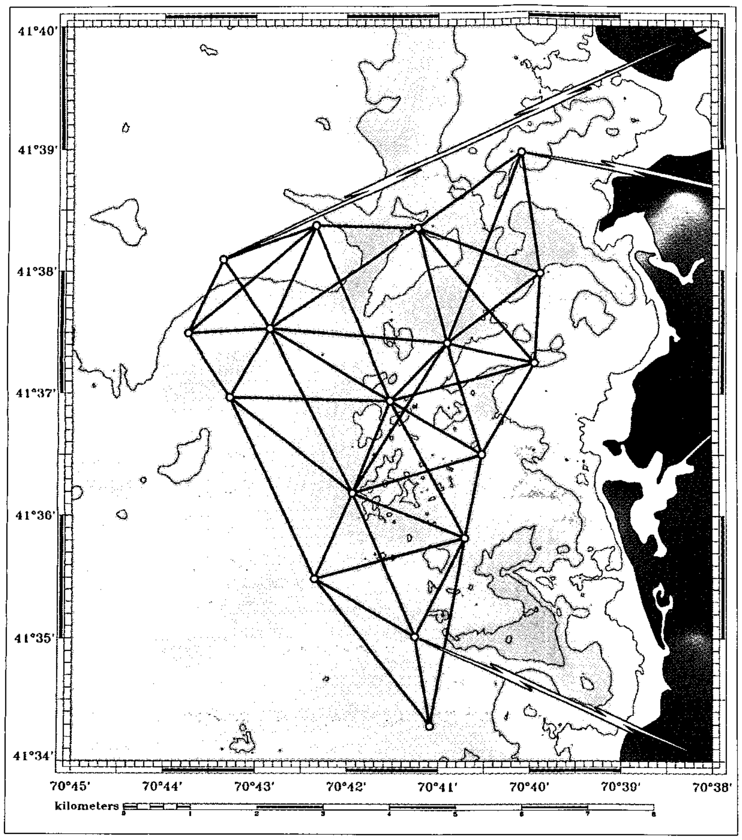
Figure 1. *Seaweb underwater acoustic networking enables data telemetry and remote control for deployable autonomous distributed systems (DADS) and other autonomous peripherals. Gateways to manned control centers include radio links to space or shore and telesonar links to ships.*

Telesonar and Seaweb experimentation addresses the many aspects of this problem, including propagation, signaling, transducers, modem electronics, networking, command-center interfacing, and transmission security. The major sea tests have included Seawebs '98, '99, and 2000.

EXPERIMENT OBJECTIVES AND APPROACH

Telesonar acoustic links form the digital network of fixed and mobile nodes. Operational objectives mandate reliability, energy efficiency, deployability, interoperability, flexibility, affordability, and security. Thus, telesonar links must be environmentally and situationally adaptive, with provision for bidirectional asymmetry. The Seaweb backbone is a set of autonomous stationary nodes (e.g., sensor nodes, repeater nodes, and master nodes). Master nodes collect data from the sensor nodes and forward to the gateways and vice versa. Seaweb peripherals include mobile nodes (e.g., AUVs). Seaweb gateways connect with command centers submerged, afloat, ashore, and aloft, including access to terrestrial, airborne, and space-based networks. For example, a telesonobuoy serves as a radio/acoustic interface permitting satellites and maritime aircraft to communicate with submerged autonomous systems. Similarly, submarines can access offboard systems with telesonar signaling. A seaweb server resides at manned command centers and is an interface to the underwater network.

Seaweb development involves periodic concentration of resources in prolonged ocean experiments. The annual Seaweb experiments are designed to validate system analysis and purposefully evolve critical technology areas such that the state of the art advances with greater reliability, functionality, and quality of service. The objective of the Seaweb experiments is to implement and test telesonar modems in networked configurations where various modulation and networking algorithms can be exercised, compared, and con-



■ **Figure 2.** *Seaweb 2000 incrementally exercised the telesonar handshake protocol in a network context. The 17-node seaweb network delivered oceanographic data from sensor nodes to gateway nodes with line-of-sight packet radio and via cellular telephone modem. The 10 m waters of Buzzards Bay produced forward-scattered propagation with 10 ms multipath signal dispersion. Wind-driven sea surface roughness dramatically influenced quality of service by decreasing received signal energy and increasing received noise energy. Nevertheless, performance was excellent. During the final week of Seaweb 2000, the seaweb super server was remotely operated at the IEEE Oceans 2000 Conference in Providence, Rhode Island.*

clusions drawn. In the long term, the goal is to provide for a self-configuring network of distributed nodes, with network links adapting to the prevailing environment through automatic selection of the optimum transmit parameters.

The Seaweb '98, '99, and 2000 operating area is the readily accessible waters of Buzzards Bay, Massachusetts, charted in Fig. 2. An expanse of 5–15 m shallow water is available for large-area network coverage with convenient line-of-sight radio contact to laboratory facilities in western Cape Cod.[1] A shipping channel extending from the Bourne Canal provides periodic episodes of high shipping noise useful for stressing the link signal-to-noise ratio (SNR) margins.

Seaweb development demands attention to the underlying critical issues of adverse transmission channel, asynchronous networking, battery-energy efficiency, transmission security, information throughput, and cost. Knowledge of the fundamental constraints on telesonar technology is converted into increasingly sophisticated modems. At the MAC layer, Seaweb employs a MACA handshake protocol uniquely suited to wireless half-duplex networking. The handshaking process permits addressing, ranging, channel estimation, adaptive modulation, and power control.

INITIALIZATION AND ROUTING

Since the network in consideration is an ad hoc network, an initialization algorithm is needed to establish preliminary connections autonomously. This algorithm is based on polling and as such it guarantees connectivity to all the nodes that are acoustically reachable by at least one of their nearest neighbors. During initialization, the nodes create *neighbor tables*. These tables contain a list of each node's neighbors and a quality measure of their link, which can be the received SNR from the corresponding neighbor. The neighbor tables are then collected by the master node and a routing tree is formed.

Optimum routes are determined with the help of a genetic algorithm-based routing protocol [11]. The routing protocol tries to maximize the lifetime of the battery-powered network by minimizing the total energy consumption of the network. The minimum energy required to establish reliable communication between two nodes is used as the link distance metric. A master node collects the link cost information from the network nodes, determines optimum routes, and sends the routing information back to the nodes. The optimization algorithm favors multihop links at the expense of increased delay.

The performance of acoustic links between nodes can degrade, and even a link can be permanently lost due to a node failure. In such cases, the network should be able to adapt itself to the changing conditions without interrupting the packet transfer. This robustness can be obtained by updating the routes periodically.

In the current design, the master node creates a routing tree depending on the neighbor tables reported by its nodes. If a node reports that a link's performance has degraded or it is no longer available, the master node selects new routes that take the place of the failed link. The changes in the routing tree are reported to all related nodes. This procedure ensures that nodes won't attempt to use a failed link. In this way, unnecessary transmissions that increase battery consumption are avoided.

MEDIA ACCESS PROTOCOL

The media access protocol for Seaweb is based on the MACA protocol, which uses RTS-CTS-DATA exchange. The network employs the stop-and-wait ARQ scheme [6]. If the source cannot receive a CTS from the destination after a predetermined time interval, it repeats RTS. If after K trials of RTS the source cannot receive a CTS, it decides that the link is no longer available and returns to low power state. If the source receives a CTS, it immediately transmits the data packet. The RTS/CTS exchange is used to determine the channel conditions, and this information is used to set the acoustic modem parameters such as output power level. An ACK signal is sent by the destination upon receipt of a correct data packet, to provide positive acknowledgment to the source in the data link layer. The protocol can also handle negative acknowledgments depending on the operation mode selected by the user. Figure 3 illustrates the MAC protocol.

If two nodes send an RTS to each other, unnec-

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[1] *The laboratory facilities of Benthos, Inc. have been used as a command center for coordinating the Seaweb tests.*

essary retries may occur because both nodes will ignore the received RTS command. Each node will then wait for the other node to send a CTS for a timeout duration, and retransmit their RTS packet. This problem is solved by assigning priority to the packets that are directed toward the master node.

CONCLUDING REMARKS

In this tutorial article, we present an overview of basic principles and constraints in the design of reliable shallow water acoustic networks that may be used for transmitting data from a variety of undersea sensors to onshore facilities. Major impediments in the design of such networks are considered, including:

- Severe power limitations imposed by battery power
- Severe bandwidth limitations
- Channel characteristics including long propagation times, multipath, and signal fading

Multiple access methods, network protocols, and routing algorithms are also considered.

Of the multiple access methods considered, it appears that CDMA, achieved by either frequency hopping or direct sequence, provides the most robust method for the underwater network environment. Currently under development are modems that utilize these types of spread-spectrum signals to provide multiple access capability to the various nodes in the network. Simultaneous with current modem development, there are several investigations on the design of routing algorithms and network protocols.

The design example of the shallow water network employed in Seaweb embodies the power and bandwidth constraints that are so important in digital communication through underwater acoustic channels. As an information system compatible with low bandwidth, high latency, and variable quality of service, Seaweb offers a blueprint for the development of future shallow water acoustic networks. Experimental data that will be collected over the next several years will be used to assess the performance of the network and possibly validate a number of assumptions and trade-offs included in the design. Over the next decade, significant improvements are anticipated in the design and implementation of shallow water acoustic networks as more experience is gained through at-sea experiments and network simulations.

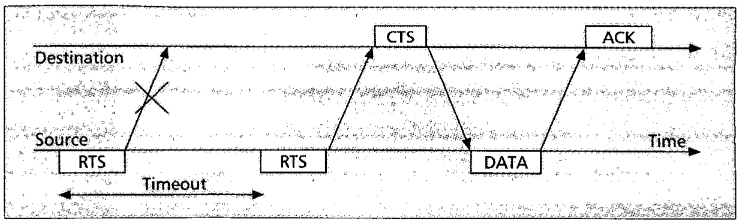

Figure 3. *The source node starts the MAC layer handshake protocol by sending an RTS packer the destination node. If the RTS packet is lost in the channel, the source node retransmits the RTS packet after a timeout duration equal to the round-trip duration of a header-only packet (e.g., RTS, CTS, or ACK), and calculated using the range information in the neighbor tables. When the destination node receives the RTS, it replies with a CTS packet. Upon reception of the CTS packet by the source, the DATA packet, which contains a header and the information, is sent to the destination. The handshake is completed with the ACK packet sent by the destination to denote error-free reception of the DATA packet.*

REFERENCES

[1] J. Catipovic, D. Brady, and S. Etchemendy, "Development of Underwater Acoustic Modems and Networks," *Oceanography*, vol. 6, Mar. 1993, pp. 112–19.

[2] M. Stojanovic, "Recent Advances In High-Speed Underwater Acoustic Communications," *IEEE J. Oceanic Eng.*, vol. 21, Apr. 1996, pp. 125–36.

[3] D. B. Kilfoyle and A. B. Baggeroer, "The State of the Art In Underwater Acoustic Telemetry," *IEEE J. Oceanic Eng.*, vol. 25, 2000, pp. 4–27.

[4] T. B. Curtin *et al.*, "Autonomous Oceanographic Sampling Networks," *Oceanography*, vol. 6, no. 3, Mar. 1993, pp. 86–94.

[5] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*, New York: Wiley, 1995.

[6] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater Acoustic Networks," *IEEE J. Oceanic Eng.*, vol. 25, Jan. 2000, pp. 72-83.

[7] E. M. Sozer *et al.*, "Direct Sequence Spread Spectrum Based Modem for Under Water Acoustic Communication and Channel Measurements," *Proc. OCEANS '99*, Nov. 1999.

[8] P. Karn, "MACA - A New Channel Access Method for Packet Radio," *ARRL/CRRL Amateur Radio 9th Comp. Network Conf.*, Sep. 1990.

[9] V. Bharghavan *et al.*, "MACAW: A Media Access Protocol for Wireless LAN's," *ACM SIGCOMM*, Aug. 1994, pp. 212–25.

[10] J. A. Rice, "Telesonar Signaling and Seaweb Underwater Wireless Networks," *Proc. NATO Symp. New Info. Processing Techniques for Mil. Sys.*, Istanbul, Turkey, Oct. 9–11, 2000

[11] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Initialization and Routing Optimization for Ad Hoc Underwater Acoustic Networks," *Opnetwork'00*, Washington, DC, Aug. 2000.

BIOGRAPHIES

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