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 QoS 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 paper considers several aspects in the design of shallow water acoustic networks that maximize throughput and reliability while minimizing power consumption.

Keywords: underwater, acoustic, communications, network media access control (MAC), routing, ad hoc, seaweb

1 Introduction

In the last two decades, underwater acoustic (UWA) communications technology has progressed significantly. Communication systems with increased bit rate and reliability now enable real-time

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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 on-shore 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 long delay between data acquisition and recovery can be reduced by using expendable or reusable communication probes as in the EMMA [2], and GEOSTAR [3] systems. Both systems have ocean bottom sensors and a number of probes that have radio communication equipment. The data collected by sensors are carried to the surface with probes at preprogrammed intervals or after some interesting observation. After surfacing, the probe sends the data to an on-shore user via satellite. The release of the probes can also be forced by sending acoustic signals from a near-by ship. These systems provide quasi-real time data collection. However, lack of bi-directional communication links, and the high cost of probes limit their usage.

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 bi-directional acoustic communication between nodes such as autonomous underwater vehicles (AUVs) and fixed sensors. An RF link connects the network to a surface station which can further be connected to terrestrial networks, such as the Internet, through an RF link. On-shore 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 are 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 UWA networks is the limited energy supply. Whereas the batteries of a wireless modem can be easily 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 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 grid. 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.

2 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.

The available bandwidth of an UWA channel depends critically on transmission loss, which increases with both range and frequency, and severely limits the available bandwidth [4], [5]. For example, long-range systems that operate over several tens of kilometers may have a bandwidth

Table 1: Summary of performance metrics for some UWA modems presented in the literature [5]. Subscript "S" indicates a shallow water result, while "D" indicates a deep water result, generally a vertical channel.

Type	Year	Data Rate (bps)	Bandwidth (kHz)	Range (km)
FSK	1984	1200	5	3.0_S
FSK	1991	1250	10	2.0_D
FSK	1997	2400-600	5	$10.0_D - 5.0_S$
Coherent	1989	500000	125	0.06_D
Coherent	1993	600 - 300	0.3 - 1	$89_S - 203_D$
Coherent	1994	20	20	0.9_S
Coherent	1998	1670 - 6700	2 - 10	$4.0_S - 2.0_S$

of only a few kHz, while a short-range system operating over several tens of meters may have more than a hundred kHz bandwidth [6]. Within this limited bandwidth, the acoustic signals are subject to time-varying multipath [4], 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 the 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 non-coherent frequency shift keying (FSK) signals for achieving reliable communication. Since FSK demodulation is based on energy detection, it does not require phase tracking, which is a very difficult task in Doppler-spread channels. The multipath effects are eliminated by inserting guard periods between successive pulses to ensure that the reverberation vanishes before each subsequent pulse is to be received. In addition, to avoid Doppler effects, some guard bands are employed between frequency tones. By varying the values of the guard bands, the communication signals can be matched to the channel characteristics, providing an adaptive modem structure. Table 1 presents some data on the non-coherent FSK modems described in the literature.

Although non-coherent 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 towards coherent modulation techniques.

Today, with the availability of powerful digital signal processing devices, fully coherent PSK modulation is practical for underwater communications. Equalizers are used to undo the effects of ISI, instead of trying to avoid or suppress it. When combined with explicit phase tracking loops, such as phase locked loops (PLLs), decision-feedback equalizers can provide high data throughput [7]. Other similar structures that use transversal filters and various adaptation algorithms are also reported in the literature. A summary of coherent systems is listed in Table 1.

Current research is focused on DSP algorithms with decreased complexity and multiuser modems that can operate in a network environment.

3 Underwater Acoustic Networks

Information networks are designed in the form of a layered architecture [8]. The first three layers of this hierarchical structure are the physical layer, the data link control layer, and the network layer.

The function of the physical layer is to create a virtual link for transmitting a sequence of logical information (bits 0 and 1) between pairs of nodes. The information bits are converted into acoustic signals (in case of UWA networks), which are transmitted through the acoustic channel. At the receiving node, the physical layer converts the channel-corrupted signals back into logical bits. The modem structures that can be used in the physical layer of an acoustic network were discussed in the previous section.

The second layer in the hierarchical structure is the data link control (DLC) layer. The DLC layer is responsible for converting the unreliable bit pipe of the physical layer into a higher level error-free link. For this purpose DLC employs two mechanisms: framing and error correction control. Framing is accomplished by adding header information, which consists of a synchronization preamble, and source and destination addresses at the beginning of the information sequence, and cyclic redundancy check (CRC) bits, at the end. The CRC bits are formed from the bits in the packet and are used for error correction control.

At the receiver side, the DLC performs a check using the CRC field to detect errors in a packet. If the CRC fails, it may ask for a retransmission depending on the automatic repeat request (ARQ) protocol. Some widely used ARQ schemes are stop & wait, go-back-N, and selective repeat. These protocols control the logical sequence of transmitting packets between two nodes and acknowledging the correctly received packets. ARQ procedures form the logical link control (LLC) sublayer of the DLC. If the network is based on multiaccess links, rather than point-to-point links, additional measures must be taken to orchestrate the access of multiple sources to the same medium. These measures are called media access control (MAC) . Commonly used MAC protocols are the Aloha protocol, the carrier sense media access (CSMA) protocols, and token protocols. These protocols form the MAC sublayer of DLC.

The layer above the DLC layer is the network layer. The main function of the network layer is to transfer information packets to their final destination, which is called routing. Routing involves finding a path through the network and forwarding the packets from the source to the destination along this path. If a route is established at the beginning of a transaction and all the packets follow this path, the network is called a virtual circuit switching network. If a new path is determined for each packet of the same transaction, then the network employs datagram switching. In case of datagram switching, packets may arrive to the destination out of order. Therefore, the network layer should reorder the packets before passing them to a higher level.

The network layer selects optimal routes by minimizing the end-to-end path distance. The distance metric can be the delay, the number of hops, required energy, or some other "distance" measure. Some well known static routing algorithms are the Dijkstra algorithm and the Bellman-

Ford algorithm. In dynamic environments, the routes provided by these static algorithms are modified as the "distance" metrics change.

In the following subsections, we review the methods and protocols used in the DLC layer and network layer, together with their applicability to UWA networks. We also discuss possible network topologies, which is an important constraint in designing a network protocol.

3.1 Network Topologies

There are three basic topologies that can be used to interconnect network nodes: centralized, distributed, and multihop topology [9]. 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 [9]. 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 support peer-to-peer links. 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 adjacent nodes, which is called the *near-far* problem [9].

Multihop peer-to-peer networks are formed by establishing communication links only between neighboring nodes. Messages are transfered from source to destination by hopping packets along a multi-node route. 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. Network topology is an important parameter that determines the energy consumption [10]. A simplified scenario in which a number of nodes and a master node arranged linearly along a line is considered. The nodes are uniformly distributed and each node tries to send its packets to the master node. Two extreme communication strategies are possible in this scenario. In the first strategy, each node has a direct access to the master node (fully connected topology). In the second strategy, each node transmits only to its nearest neighbor, who then relays the information toward the master node (multihop peer-to-peer topology). The energy consumption curves for both of these cases is plotted as a function of the total distance spanned by the network in Figure 1. Dashed curves represent the case of direct access, which obviously requires more energy. For direct access, inclusion of each additional node results in an increase in total energy. For relaying, the situation is reversed; inclusion of each additional node decreases the total energy consumption because the additional node serves as an additional relay along the same distance.

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

3.2 Multiple Access Methods

In many information networks, communication is bursty, and the amount of time 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 methods. Frequency division multiple access (FDMA), divides the available frequency band into subbands and assigns each subband to an individual user. Due to the severe

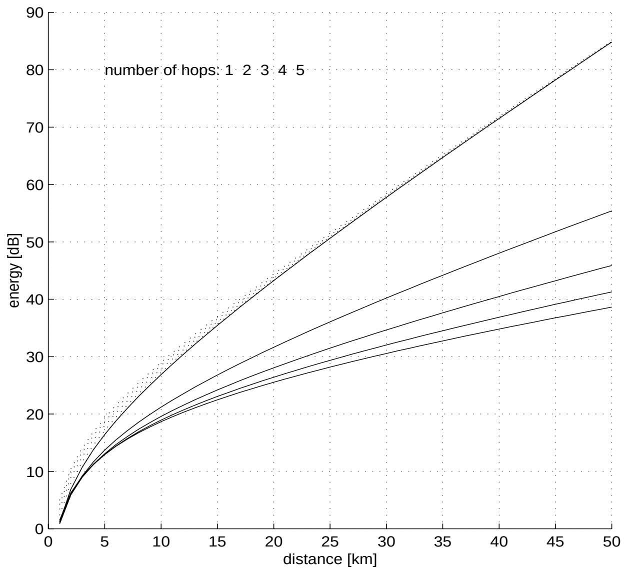

Figure 1: Total (normalized) energy needed to transmit a packet from each of the network nodes to the master node. Solid curves represent relaying; dotted curves represent direct-access. The parameter on the curves is the number of hops. For relaying, the number of hops increases from the top curve downwards; although more packets are sent when there are more hops, total energy consumption is lower. For direct access, there is little difference between the curves, and the situation is reversed: the number of hops increases from 1 for the lowest energy consumption to 5 for the highest.

bandwidth limitations and vulnerability of narrow band 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 limit 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 provides resistance to frequency selective fading, and exploits the time diversity present in the UWA channel by employing rake filters at the receiver in the case of DS-CDMA [11]. Spread spectrum signals can be used for resolving collisions at the receiver by using multiuser detectors [12]. By this way, the number of retransmissions and energy requirements of the system can be reduced. This property both reduces battery consumption and increases the throughput of the network. Also, the power requirement of CDMA systems may be less than one tenth that of TDMA [13]. In conclusion, CDMA is a promising multiple access technique for shallow water acoustic networks.

3.3 Media Access Control (MAC) Protocols

Since the number of channels (time frames, frequency bands, or spreading codes) offered by a multiple access method can be much less than the total number of users in a network environment, the same channel is assigned to more than one user. If these users access the channel at the same time, their signals overlap and may be lost (packet collision). Likewise, most underwater acoustic modems are half-duplex in nature, and signals arriving during a transmission are lost, and must also be treated as packet collisions. Media access control (MAC) protocols are used to avoid information loss due to packet collisions.

A group of MAC protocols, such as the ALOHA protocol, does not try to prevent collisions but detects collisions and retransmits lost packets. The original ALOHA protocol is based on random access of users to the medium [14]. Whenever a user has information to send, it transmits it immediately. An acknowledgment (ACK) is sent back by the receiver if the packet is received without errors. Due to the arbitrary transmission times, collisions occur and packets are lost. Slotted ALOHA is an enhanced version of the ALOHA protocol, where the time frame is divided into time slots. When a node wants to send a packet, it waits until the next time slot and then begins transmission. Restricting packet transmission to predetermined time slots decreases the probability of collisions [9]. As in the case of TDMA, ALOHA protocol is inefficient for UWA environment due to slow propagation. Also, the need for retransmissions increases the power consumption of the network nodes and reduces the lifetime of the network.

The number of retransmissions can be reduced if the MAC protocol uses a priori information about the channel state. The media access methods based on this idea are called Carrier Sense Multiple Access (CSMA) [9]. Details and various forms of this method can be found in [15]-[18]. The CSMA method tries to avoid the collisions by listening for a carrier in the vicinity of the transmitter. However, this approach does not avoid collisions at the receiver [19]. Let us consider a network formed by three users as shown in Figure 2. The circles around each node shows the communication range of that node. Assume that node A is sending a packet to node B. At the same time, node C listens to the channel and because it is out of the range of A and does not detect the carrier of A, it begins transmission. This creates a collision at B, which is the receiver node. Node A was hidden from node C. This situation is called the *hidden node* scenario [19]. To enable B to hear both messages, node C should defer its transmission. However, if the destination of the packet of C is not B, there is no reason to defer the transmission, provided that node B has the capability to deal with the interference generated by the signal from C [19]. In the case of B sending a packet to A, C detects a carrier. This creates an *exposed node* situation, where C is exposed to node B.

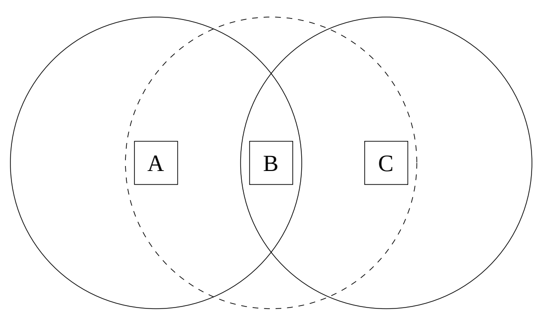

Figure 2: Node A can communicated with node B, but not with node C. B can communicated with both A and C.

CSMA cannot solve these problems without adding a guard time between transmissions that is proportional to the maximum propagation time present in the network. The extensive propagation delays in underwater channels can cause this method to become very inefficient. If we consider an underwater acoustic network with a maximum range of 10 km, a data rate of 1 kbps, and a packet size of 1000 bits, the transmission delay and the maximum propagation delay become 1 s and 6.7 s, respectively. In this situation, most of the time the channel will be idle, which results in low throughput.

The multiple access with collision avoidance (MACA) protocol was proposed by Karn [20] to detect collisions at the receiver as an alternative to CSMA. This protocol 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 which contains the length of the message that is to be sent. If B receives the RTS, it sends back a CTS command which also contains the length of the message. As soon as A receives CTS, it begins transmission of the data packet. A node that overhears an RTS (C in this case) defers long enough to let node A receive the corresponding CTS. Also, any node that overhears a CTS defers its transmission for the length of the data packet to avoid collision. If a node overhears an RTS but not a CTS, it decides that it is out of range of the receiver, and transmits its own packet. Therefore, this protocol can solve both the hidden and the exposed node problems. The nodes can probe the channel during the RTS-CTS exchange [20]. 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 can prevent collisions before they occur. The RTS-CTS exchange adds overhead but the reduction of retransmissions can compensate for this increase.

The MACAW protocol was proposed by Bharghavan [19] to improve performance and reliability of the MACA protocol. Instead of creating error-free, reliable point-to-point links with the DLC layer by use of acknowledgments, 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. For this purpose, an 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 [19] 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 assessed.

In [21], the authors show that the performance of protocols based on RTS/CTS exchange can degrade due to the collision of control packets (RTS/CTS), especially in the case of high propagation and transmission delay. Dual busy tone multiple access (DBTMA) protocol is proposed to reduce the packet collision probability. In this protocol, the single shared channel is divided into two subchannels: a data channel and a control channel. Control packets are transmitted on the control channel, while data are carried on the data channel. In addition, two out-of-band tones are introduced to indicate that a node is transmitting on the data channel (BT_t), and a node is receiving on the data channel (BT_r). There are two important limitations researchers face if this protocol is employed in an UWA network where energy and bandwidth are scarce. First, the use of additional tones increases the energy consumption of network nodes. Second, the divided bandwidth decreases the data throughput of nodes. However, due to the reduced number of collisions, the total energy consumption may be reduced, while network throughput can be increased.

3.4 Automatic Repeat Request (ARQ) Methods

Automatic repeat request (ARQ) is used in the data link control layer to request the retransmission of erroneous packets. The simplest ARQ scheme that can be directly employed in a half-duplex UWA channels 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 the 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 time-out 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 as discussed in Section 3.3.

3.5 Routing Algorithms

As previously indicated, 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 data base which 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 pre-existing infrastructure. These types of networks are called *ad hoc* networks [22].

In *ad hoc* networks the main problem is to obtain the most recent state of each individual link in the network, so as 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. In a recent paper [23], the authors compared four *ad hoc* network routing protocols presented in the literature:

- Destination Sequence Distance Vector (DSDV) [24]
- Temporally Ordered Routing Algorithm (TORA) [25]
- Dynamic Source Routing (DSR) [26]
- Ad Hoc On-Demand Distance Vector (AODV) [27]

DSDV maintains a list of *next hops* for each destination node which belongs to the shortest distance route. The protocol requires each node to periodically broadcast routing updates to maintain routing tables.

TORA is a distributed routing algorithm. The routes are discovered on-demand. This protocol can provide multiple routes to a destination very quickly. The route optimality is considered as a second priority and the routing overhead is reduced.

DSR employs source routing; that is, the route of each packet is included in its header. Each intermediate node that receives the packet checks the header for the next hop and forwards the packet. This eliminates the need for intermediate nodes to maintain best routing information to route the packets.

AODV uses the on-demand route discovery and maintenance characteristic of DSR and employs them in a hop-by-hop routing scheme instead of source routing. Also, periodic updates are used in this protocol.

In a mobile radio environment DSR provides the best performance in terms of reliability, routing overhead, and path optimality [23]. The effect of long propagation delays and channel asymmetries caused by power control are issues that need to be addressed when considering application of these network routing protocols to UWA channels.

4 Evolution of UWA Networks

Two types of applications have guided the evolution of underwater networks so far. One is gathering of environmental data, and the other is surveillance of an underwater area. In the first case, the network consists of several types of sensors, some mounted on fixed moorings and others mounted on moving vehicles. This type of network is called an Autonomous Ocean Sampling Network (AOSN), where the word 'sampling' implies collecting the samples of oceanographic parameters such as temperature, salinity, underwater currents, etc. 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. In particular, mapping may focus on detection of warfare objects. An example of such a network, called Seaweb, will be described in more detail in Section 5.

An AOSN is formed by a number of autonomous underwater vehicles (AUVs), moorings, and surface buoys. The AUVs traverse an ocean area spanned by the network nodes (moorings and surface buoys) collecting scientific data. The coordination of the AUVs is handled from a central location, which can either be at one of the network nodes and/or on-shore. AUVs relay key observations and their status to the central location. After evaluating the incoming data, the central location sends control signals to the AUVs through the network nodes. The acoustic communication between the AUVs and the network nodes is designed so that it does not require high data throughput. More complete data sets are transferred to the on-shore control center through a radio channel when AUVs dock to a mooring. The control center is connected to a backbone such as the Internet, so that a scientist can reach the sampling network in real-time. An important limitation observed during the tests of the AOSN was the impossibility for the AUVs to instantly respond to commands due to the high-latency environment [28]. As a result of the highly variable acoustic channel, network connections to AUVs were occasionally lost. Therefore, some level of automation is needed in the AUVs to avoid disastrous events, which may occur if the last command sent to an AUV directs it toward an obstacle and the connection is lost.

A deep water acoustic local area network (ALAN) was deployed in Monterey Canyon, California, for long-term data acquisition and ocean monitoring from multiple ocean bottom sources [1]. A centralized network topology was employed with a hub on the surface. The MAC protocol was based on TDMA where time slots were determined adaptively based on estimated latency. Because this protocol relies on correct estimation of the round-trip propagation times, any error in the estimation process decreases the throughput of the system by causing retransmissions.

The evolution of research on underwater acoustic networks has followed the usual layered architecture. Most work to this date has been performed on the physical layer and multiple access techniques. The data link layer protocols have been addressed to a lesser extent, and the work has only begun on the network layer and routing algorithms [5]. In all of these areas, the focus of research has been on adapting the well-known theoretical concepts to the requirements and constraints of the underwater acoustic channels.

Typically, packet transmission in a store-and-forward network is considered in most of the underwater acoustic networks. The design of automatic repeat request (ARQ) protocols is influenced by the long propagation times in underwater channels. In [29], the authors proposed a shallow water acoustic local area network (S-ALAN) protocol, which is a modified version of ARPA-supported packet radio network (PRN) protocol. The S-ALAN differs from PRN in the routing algorithm and the data transmission medium. In contrast to PRN, which uses datagram switching over a single channel, S-ALAN employs virtual circuit switching using three separate channels (frequency bands) and selective repeat ARQ. When a network node gathers enough information to send to the control center, it issues a request to set up a virtual circuit. When the setup request reaches the destination node, the destination node assigns transmit data, receive data, and acknowledgment channels for all the nodes in the virtual circuit and reports the final configuration back to the source node. The use of three separate channels enables the network to fully utilize the ARQ scheme.

A peer-to-peer communication protocol has been developed to control AUVs [30] based on carrier sense multiple access with collision avoidance (CSMA/CA). Since the CSMA/CA protocol relies on acknowledgments, the channel stays idle for an amount proportional to the round trip propagation time. Due to the long propagation delays in UWA channels, this protocol has a low throughput. On the other hand, it is highly reliable.

A recent media access protocol proposed for shallow water acoustic networks is presented in [10]. The protocol is based on the MACA protocol and employs a Stop & Wait ARQ scheme. 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. The details of this network are given in the following section.

The routing optimization problem for a shallow water acoustic network is addressed in [31]. The genetic algorithm based routing protocol tries to maximize the life time 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 authors showed that the optimization algorithm favors multihop links at an expense of increased delay.

5 SEAWEB

Seaweb is an acoustic network for communications and navigation of deployable autonomous undersea systems [32]. The US Navy incorporated seaweb networking in the June 2001 Fleet Battle Experiment India (FBE-I). The seaweb installation charted in Figure 3 was part of the overall FBE-I joint forces architecture for command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) providing wide-area connectivity, enhanced bandwidth, and reachback capability. Seaweb reliably supported asynchronous networking for an improved 688-class (688I) fast-attack nuclear submarine mobile node and two deployable autonomous distributed system (DADS) nodes. Two moored radio-acoustic communications (racom) buoy gateway nodes provided line-of-sight radio links to a shore station having terrestrial internet connection to an anti-submarine warfare (ASW) command center (ASWCC) located ashore. In addition, ten undersea repeater nodes highlighted the flexible architecture, indicating expandability and potential area coverage. The network performed reliably with no hardware failures and no lost transmissions. Seaweb supported internet protocol (IP) delivery of automated ASW contact reports from the DADS sensors to shore, and command and control (C2) on the IP backlink. Naval messages to and from the submarine via seaweb protocols permitted assured access at tactical depth. The fifteen-node FBE-I seaweb system extended Naval network-centric operations into the undersea battlespace. Analysts executed numerous communication and navigation tests, and proved that the FBE-I network design was overly conservative and could have supported even greater area coverage and traffic load.

5.1 Concept of Operations

Telesonar wireless acoustic links interconnect distributed undersea instruments, potentially integrating them as a unified resource. Seaweb is the realization of an undersea telesonar network [10] of fixed and mobile nodes, with various interfaces to manned command centers. The architectural flexibility afforded by seaweb wireless connections permits the network designer to allocate an arbitrary mix of node types with a node density and area coverage appropriate for the given telesonar propagation conditions and for the mission at hand. The concept of operations assumes that the majority of network nodes are inexpensive, autonomous, battery-limited devices deployed from submarine, ship and aircraft, or from unmanned undersea vehicles (UUVs) and unmanned aerial vehicles (UAVs).

Seaweb networks support asynchronous data communications from autonomous nodes to command centers. On the backlink, seaweb allows remote command & control of instruments associated with the autonomous nodes. Additionally, network activity supports acoustic navigation and geolocalization of undersea nodes as a natural by-product of telesonar ranging signals. More generally, seaweb networking permits wireless transmissions between member nodes in the network using established routes or via an intervening cellular node.

Seaweb enables future Naval capabilities in littoral ASW and undersea autonomous operations. A significant dual-use of seaweb is communication and navigation for oceanographic surveys and environmental assessment. Certainly, a major potential benefit of the technology is cross-system, cross-platform, cross-mission interoperability, providing enormous added value to otherwise solitary systems. For example, a UUV mobile node operating within a grid of fixed sensor nodes benefits from the established network topology for situational awareness, navigation, and communications via gateway nodes to distant command centers. Conversely, UUVs add value to the fixed grid for sensor deployment, search, survey, water-column sampling, pop-up racom gateway communications, etc.

The initial motivation for seaweb is a requirement for wide-area surveillance in littoral waters. These sensors operate in 50- to 300-m waters with node spacing of 2 to 5 km. Sensor nodes generate concise ASW contact reports that seaweb routes to a master node for field-level data fusion [33]. Primary network packets are contact reports with about 1000 information bits [34]. Sensor nodes asynchronously produce these packets at a variable rate dependent on the receiver operating characteristics (ROC) for a particular sensor suite and mission. The master node communicates with manned command centers via encrypted gateway nodes such as a racom sea-surface buoy linked with space satellite networks. Following ad hoc deployments, the seaweb network self-organizes including node identification, clock synchronization on the order of 0.1 to 1.0 s, node geo-localization on the order of 100 m, assimilation of new nodes, and self-healing following node failures.

As a fixed grid of inexpensive interoperable sensor nodes and repeater nodes, this is the most fundamental seaweb operating mode based on a stable topology that periodically adjusts itself to optimize overall network endurance and quality of service (QoS). The fixed seaweb topology provides an underlying cellular network suited for supporting an AOSN [35], including communication and navigation for UUV mobile nodes. The cellular architecture likewise provides seamless connectivity for submarine operations at speed and depth in a manner not unlike terrestrial cellular telephone service for automobiles.

5.2 Developmental Approach

The concept of operations emphasizes simplicity, efficiency, reliability, and security, and these attributes therefore govern the design philosophy for seaweb development. Research is advancing telesonar modem technology for reliable underwater signaling by addressing the issues of (a) adverse transmission channel; (b) asynchronous networking; (c) battery-energy efficiency; (d) transmission security; and (e) cost.

Despite a concept of operations emphasizing simplicity, seaweb is a multi-faceted system and its development is a grand challenge. The high cost of sea testing and the need for many prototype nodes motivate extensive engineering system analysis. Simulations using an optimized network engineering tool (OPNET) with simplified ocean acoustic propagation assumptions permit laboratory refinement of networking protocols [34] and initialization methods [36]. Meanwhile, controlled experimentation in actual ocean conditions incrementally advances telesonar-signaling technology [37].

Seaweb development balances the desire for rapid increases in capability and the need for stable operation in support of applications that are themselves developmental. This balance is achieved by an annual cycle culminating with the late-summer Seaweb experiment (i.e., Seaweb '98, Seaweb

’99, Seaweb 2000, ...).

The objective of the annual Seaweb experiments is to exercise telesonar modems in networked configurations where various modulation and networking algorithms can be assessed. In the long-term, the goal is to provide for a self-configuring network of distributed assets, with network links automatically adapting to the prevailing environment through selection of the optimum transmit parameters. A full year of hardware improvements and in-air network testing helps ensure that the incremental developments tested at sea will provide tractable progress and mitigate overall developmental risk. In preparation for Seaweb experimentation, multiple contributing projects conduct relevant research during the first three quarters of the fiscal year. The 4th-quarter Seaweb experiment then implements and tests the results from these research activities with a concentration of resources in prolonged ocean experiments. The products of the annual Seaweb experiment are major capability upgrades for integrated seaweb server software, telesonar modem seaweb firmware, and telesonar modem hardware. The annual Seaweb experiment also transitions these upgrades into participating application systems. After the annual Seaweb experiment yields a stable level of functionality, the firmware product can be further exercised and refinements instituted during system testing and by spin-off applications throughout the year. For example, in year 2001, Seaweb 2000 technology enabled the March-June FRONT-3 ocean observatory on the continental shelf east of Long Island, NY [38]. These applications afford valuable long-term performance data that are not obtainable during Seaweb experiments when algorithms are in flux and deployed modems are receiving frequent firmware upgrades. At the conclusion of the Seaweb experiment, the upgraded seaweb capability reaches stability suitable for use with the continuing development of the various application systems during the following year. Meanwhile, the annual cycle repeats, beginning with research and preparations for the next Seaweb experiment. And so, seaweb capability increases in an incremental manner.

The seaweb architecture of interest includes the physical layer, the media-access-control (MAC) layer, and the network layer. These most fundamental layers of communications functionality support higher layers, collectively identified here as the "client" layer. The client layer tends to be application specific and is not the direct responsibility of telesonar modems or the seaweb network.

5.3 Telesonar Modems and the Physical Layer

The US Navy has been developing *telesonar* modems designed to function at low bit-rates with high reliability and modest processing [39], [40]. The basis for this approach is the need for low-cost, energy-efficient workhorse modems suitable for the development of networking technologies [41]. From an interoperability perspective, the low bit-rate modem offers the lowest common denominator for cross-system networks that may include low-cost, expendable nodes [42], [43]. As a pair of modems establishes a low bit-rate link, they may adaptively negotiate higher bit-rate modulations if warranted by favorable propagation and available processing resources.

The present telesonar modem [44] normally uses 5 kHz of acoustic bandwidth encompassing 120 discrete MFSK bins and 8 tracking bins [45]. A basic 1-of-4 MFSK modulation carries 2400 bit/s but lacks data protection and error-correction coding (ECC). A constraint-length-9, 1/2-rate convolutional code very effectively corrects bit errors by representing binary information across multiple symbols; the 1/2-rate reduces throughput by a factor of 2. For protection against multipath-induced inter-symbol interference (ISI), the MFSK chip duration may be lengthened; the modem allows for a doubling from 25 to 50 ms resulting in another factor of 2 reduction in bit-rate. A "Doppler-tolerant" mode skips alternate MFSK bins to allow greater latitude for tracking Doppler shifts caused by node-to-node range rate. The Doppler-tolerant mode also increases robustness by doubling the acoustic energy per chip, but it also causes another halving in bit-rate. Finally, a Hadamard MFSK modulation carries 6 Hadamard codewords of 20 tones each. Interleaving the codewords across the band increases immunity to frequency-selective fading, and Hadamard coding yields a frequency diversity factor of 5 for adverse channels having low or modest spectral coherence. Hadamard signaling is effective in channels having frequency selective fading or narrowband noise. Any combination of the above options is possible. For FBE-I, a conservative modulation choice combined Hadamard MFSK, 1/2-rate convolutional coding, and 50-ms chip lengths to yield a net 300 bit/s information rate.

For all operational modes, receiving modems process the data noncoherently using a fixed-point TMS320C5410 DSP. Directional transducers can further enhance the performance of these devices [46], [47]. The present telesonar modem includes provision for a watchdog function hosted aboard a microchip independent of the DSP. The watchdog resets the DSP upon detection of supply voltage drops or upon cessation of DSP activity pulses. The watchdog provides a high level of fault tolerance and permits experimental modems to continue functioning in spite of system errors. A watchdog reset triggers the logging of additional diagnostics for thorough troubleshooting after modem recovery.

Low-bandwidth, half-duplex, high-latency telesonar links limit seaweb QoS. Occasional outages from poor propagation or elevated noise levels can disrupt telesonar links [48]. Ultimately, the available energy supply dictates service life and battery-limited nodes must be energy conserving [49]. Moreover, seaweb must ensure transmission security by operating with low bit-energy per noise-spectral-density (Eb/N0) and by otherwise limiting interception by unauthorized receivers.

Spread-spectrum modulation is consistent with the desire for asynchronous multiple-access to the physical channel using code-division multiple-access (CDMA) networking [50]. Nevertheless, the seaweb concept does not exclude time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) methods and is in fact pursuing hybrid schemes suited to the physical-layer constraints. In a data transfer, for example, a concise asynchronous CDMA dialog could queue data packets for transmission during a time slot or within a frequency band such that multi-access interference (MAI) collisions are avoided altogether.

At the physical layer, an understanding of the transmission channel is obtained through at-sea measurements [51] and numerical propagation models [52]. Knowledge of the fundamental constraints on telesonar signaling translates into increasingly sophisticated modems [53]. DSP-based modulators and demodulators permit the application of modern digital communications techniques to exploit the unique aspects of the underwater channel. To aid understanding of telesonar performance, modems automatically log physical-layer diagnostics, including signal-to-noise ratio (SNR), automatic gain control (AGC), bit-error rate (BER), and the number of corrected and uncorrected errors.

5.4 Handshake Protocols and the MAC Layer

Developmental Seaweb modem firmware implements the core features of a compact, structured protocol for secure, low-power, point-to-point, connectivity. The protocol efficiently maps MAC-layer functionality onto a physical layer based on channel-tolerant, 64-bit utility packets and channel-adaptive, arbitrary-length data packets. Seaweb firmware implements utility packet types using the basic Hadamard MFSK physical layer. These utility packet formats permit data transfers and node-to-node ranging. A richer set of available utility packets is being investigated with OPNET simulations prior to modem implementation, but seven core utility packets provided substantial networking capability for FBE-I.

The telesonar handshake protocol is suited to wireless half-duplex networking with slow propagation. Handshaking [20] asynchronously establishes adaptive telesonar links [54]. The initial handshake consists of the transmitter sending a request-to-send (RTS) packet and the receiver replying with a clear-to-send (CTS) packet. A busy signal (BSY) packet may be issued in response to an RTS when the receiver node decides to defer data reception in favor of other traffic. Following a successful RTS/CTS handshake, the data packet(s) are sent. This RTS/CTS round trip establishes the communications link and probes the channel to gauge optimal transmit power. Future firmware enhancements will support power control and the adaptive choice of data modulation method, with selection based on channel estimates derived from the RTS role as a probe signal. Telesonar links eventually will be environmentally adaptive [55], with provision for bi-directional asymmetry. Handshaking permits addressing, ranging, channel estimation, adaptive modulation, and power control.

The Seaweb 2000 core protocol implemented stop-and-wait ARQ scheme by providing either positive or negative acknowledgement of a data message. The choice of acknowledgment type depends on the traffic patterns associated with a particular network mission. Handshaking provided the means for resolving packet collisions automatically using retries from the transmitter or automatic-repeat-request (ARQ) packets from the receiver. For FBE-I, a purely negative acknowledgment was supported by the modem, implemented as an ARQ utility packet. At the client layer, the DADS client system supports positive acknowledgment through its IP implementation. Figure 4 illustrates the MAC layer protocol.

If two nodes send an RTS to each other, unnecessary 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 towards the master node, as explained below (Figure 5).

Assume that node A is a lower level node than node B; that is, A is the parent of B. Node A and node B both send RTS to each other. Due to transmission delays, packets arrive to their destinations while both nodes are waiting for a CTS packet. When node B receives the RTS, it notices that the packet is from its own destination, node A. Node B checks whether node A is its parent or child. Since node A is its parent, node B has the priority and sends a CTS packet immediately. By that time, node A receives the RTS of node B, does the same check and decides that it should wait for node B to complete its data transmission, since node B is its child. Therefore, node A puts its own data packet into a queue and waits for the CTS packet of node B.

Future implementations of seaweb firmware will retain the purely negative acknowledgment approach, as analysis has shown this to be the appropriate MAC layer implementation for long-latency, half-duplex links. For communications requiring positive acknowledgments, the Seaweb 2001 firmware includes provision for efficient delivery of a receipt (RCPT) utility packet from the destination node to the source node.

The RTS/CTS approach anticipates eventual implementation of adaptive modulation and secure addressing. The initiating node transmits a RTS waveform with a frequency-hopped, spread-spectrum (FHSS) [44] pattern or direct-sequence spread-spectrum (DSSS) [11] pseudo-random carrier uniquely addressing the intended receiver. (Alternatively, the initiating node may transmit a universal code for broadcasting or when establishing links with unknown nodes.) The addressed node detects the request and awakens from an energy-conserving sleep state to demodulate. Further processing of the RTS signal can provide an estimate of the channel scattering function and signal excess. An adaptive power-control technique determines the source level that will deliver sufficient but not excessive SNR. The addressed node then acknowledges receipt with a FHSS or DSSS acoustic response. This CTS reply specifies appropriate modulation parameters for the ensuing message packets based upon the measured channel conditions. Following this RTS/CTS handshake, the initiating node transmits the data packet(s) with nearly optimal bit-rate, modulation, coding, and source level.

5.5 Seaweb Server and the Network Layer

The seaweb backbone is a set of autonomous, stationary nodes (e.g., deployable surveillance sensors, repeaters). Seaweb peripherals are mobile nodes (e.g., UUVs, including swimmers, gliders and crawlers) and specialized nodes (e.g., bi-static sonar projectors). Seaweb gateways provide connections to command centers submerged, afloat, aloft, and ashore. Telesonar-equipped gateway nodes interface seaweb to terrestrial, airborne, and space-based networks. For example, a telesonobuoy serves as a racom interface permitting satellites and maritime patrol aircraft to access submerged, autonomous systems. Similarly, submarines can access seaweb with telesonar signaling through the underwater telephone band or other high-frequency sonar [56]. Seaweb provides the submarine commander digital connectivity at speed and depth with bi-directional access to all seaweb-linked resources and distant gateways.

At the physical and MAC layers, adaptive modulation and power control are keys to maximizing both channel capacity (bit/s) and channel efficiency (bit-kilometer/joule). At the network layer, careful selection of routing is required to minimize transmit energy, latency, and net energy consumption, and to maximize reliability and security. Seaweb experimentation underscores the differences between acoustic networks and conventional networks. Limited power, small bandwidth, and propagation latencies dictate that the seaweb network layer be simple and efficient. For compatibility with seaweb networks, the higher client layers must utilize look-up tables, data compression, forward error correction, and data filtering to minimize packet sizes and retransmissions, and to avoid congestion at the network layer.

A very significant development was the introduction of the seaweb server [57]. A seaweb server resides at manned command centers and is the graphical user interface to the undersea network. It interprets, formats, and routes downlink traffic destined for undersea nodes. On the uplink, it archives incoming data packets produced by the network, retrieves the information for an operator, and provides web-based read-only database access for client users. The server manages seaweb gateways and member nodes. It monitors, displays, and logs the network status. The server manages the network routing tables and neighbor tables and ensures network interoperability. Seaweb '99 modem firmware permitted the server to remotely reconfigure routing topologies, a foreshadowing of future self-configuration and dynamic network control. The seaweb server is a suite of software programs implemented under Linux on a laptop PC with a LabVIEW(tm) graphical user interface. A single designated "super" server controls and reconfigures the network.

Network supervisory algorithms can execute either at an autonomous master node or at the seaweb server. Seaweb provides for graceful failure of network nodes, addition of new nodes, and assimilation of mobile nodes. Essential by-products of the telesonar link are range measurement, range-rate measurement, and clock-synchronization. Collectively, these features will support network initialization, node localization, route configuration, resource optimization, and maintenance.

Node-to-node ranging employed a new implementation of a round-trip-travel time measurement algorithm with 0.1-ms resolution linked to the DSP clock rate.

As a network analysis aid, all modems now include a data-logging feature. All output generated by the telesonar modem and normally available via direct serial connection is logged to an internal buffer. Thus, the behavior of autonomous nodes can be studied in great detail after recovery from sea. Seaweb 2000 firmware logs diagnostics related to channel estimation (e.g., SNR, multipath duration, range rate, etc.), demodulation statistics (e.g., BER, AGC, intermediate decoding results, power level, etc.), and networking (e.g., data packet source, data packet sink, routing path, etc.). For seaweb applications, the data-logging feature can also support the archiving of data until such time that an adjacent node is able to download the data. For example, a designated sink node operating without access to a gateway node can collect all packets forwarded from the network and telemeter them to a command center when interrogated by a gateway (such as a ship arriving on station for just such a data download).

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. An example node table for node 3 of the network given Figure 6 is as follows:

Table 2: Node table of node 3 for the network given in Figure 6. The table contains the ID of the nodes that node 3 can communicate with a direct link. For each neighbor, the range of the node and the minimum output power required to communicate with that node is entered. The output power is in dB with respect to the maximum output power of the modem. Due to the channel characteristics, nodes at different ranges may require the same amount of output power.

Neighbor ID	Range (km)	Output Power (dB)
1	6	-9 dB
2	7	-9 dB
3	9	-3 dB

The master node decides on the primary (and secondary) routes to each destination, with routing optimization based on the genetic algorithm. Initialization ends when the master node sends primary routes to the nodes. The initialization algorithm provides either a single set of connections, or multiple connections between the nodes. Multiple connections are desirable to provide greater robustness to failures. A possible routing tree with backup routes for the network of Figure 6 is given in Figure 7.

Optimum routes are determined with the help of a genetic algorithm based routing protocol [31]. The routing protocol tries to maximize the life time 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 implementation, the network tables are created manually at the seaweb server with the help of the ranging packets. Also, the initial routes and updates are determined and reported to the network nodes by manually through the seaweb server.

6 Concluding Remarks

In this article, we presented 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 on-shore facilities. Major impediments in the design of such networks were considered, including 1) severe power limitations imposed by battery power; 2) severe bandwidth limitations; and 3) channel characteristics including long propagation times, multipath, and signal fading. Multiple access methods, network protocols, and routing algorithms were also considered.

Of the multiple access methods considered, it appears that CDMA, achieved either by frequency hopping or by 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 the multiple access capability to the various nodes in the network. Simultaneously 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 channel. 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 tradeoffs 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.

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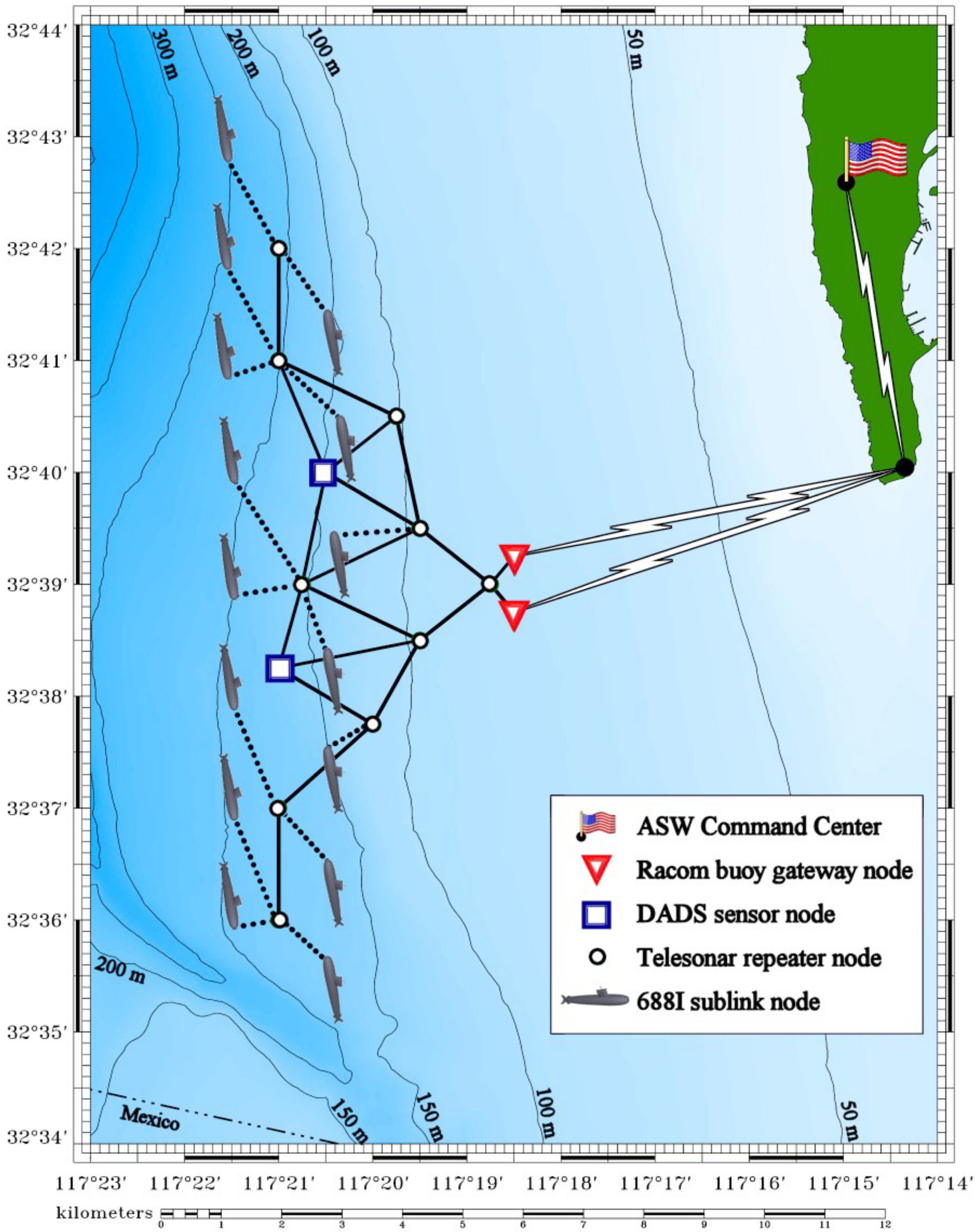

Figure 3: The FBE-I seaweb network was a 14-node undersea grid. Two nodes were prototype deployable autonomous distributed system (DADS) sensors for littoral ASW, and two nodes were moored radio/acoustic communications (racom) gateway nodes. A mobile submarine node with sublink capability had full interoperability with the seaweb network. An ASW command center served as the ashore site. US Navy personnel exercised the complete seaweb installation for four days with high reliability and no component failures.

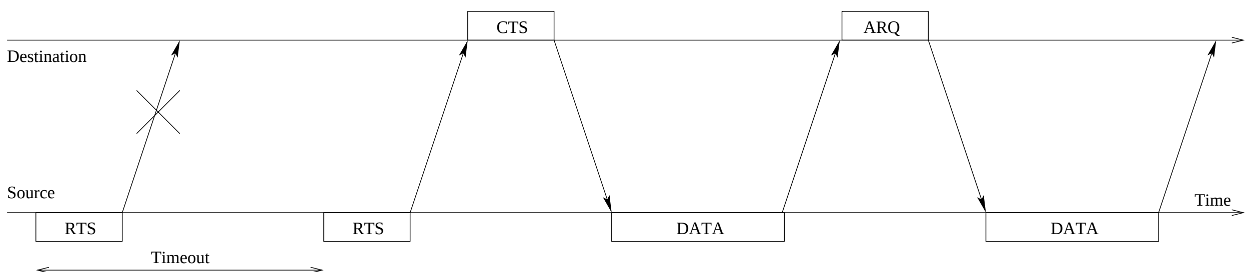

Figure 4: The source node starts the MAC layer handshake protocol by sending an RTS packet to the destination node. If the RTS packet is lost in the channel, the source node retransmits the RTS packet after a timeout duration equal to the round trip time of an header only packet (e.g. RTS, CTS or ARQ), 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 destination node issues an ARQ packet if it does not receive the DATA packet before a time-out occurs.

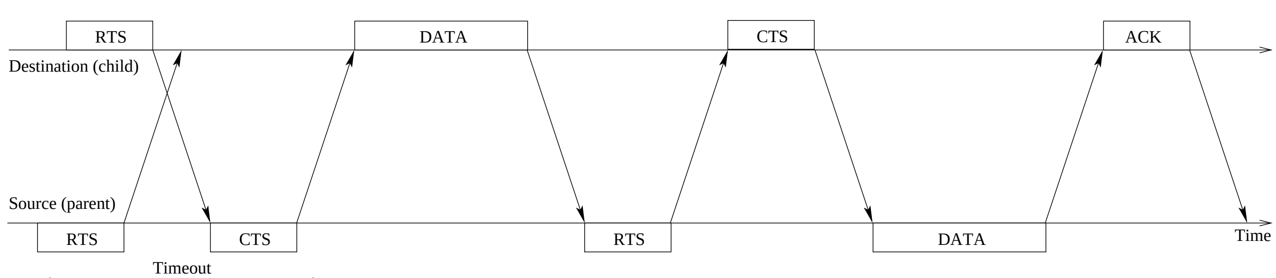

Figure 5: If two nodes send RTS packets to each other with some delay, both nodes receive the packets. When they recognize that the RTS is received from their destination, they check for the priority of the nodes. Higher level nodes, or children, have higher priority. Therefore, the parent node sends CTS telling the child to send its data. When the parent receives the data, it replies with an RTS, which also act as an acknowledgment. Then the parent sends its data to the child. This example uses positice acknowlegments (ACK).

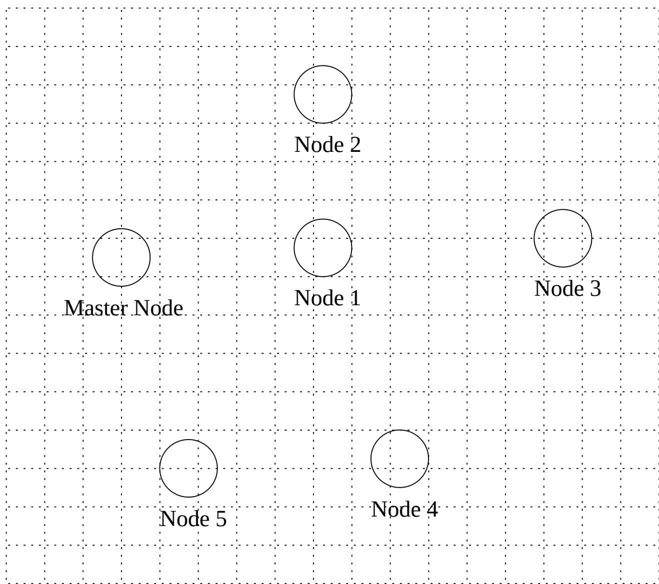

Figure 6: The network consists of a master node and five sensor nodes. The sensor nodes send information packets to the master node, which is the connection point of the network to a backbone. Master node can also send control packets to the sensor nodes.

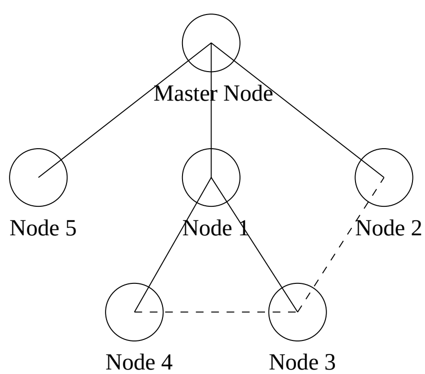

Figure 7: The routing tree is created by the master node. Master node is at the top of the tree. Sensor nodes are the leafs. Nodes 1, 2, and 5 are the children of the master node and they form the first layer of the network. Node 1 is the parent of nodes 3 and 4, which form the second layer of the network. Dashed lines are backup links that can be used in case of a failed link.