Underwater Wireless Communications: Current Achievements and Research Challenges

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While wireless communication technology today has become part of our daily life, the idea of wireless undersea communications may still seem far-fetched. However, research has been active for over a decade on designing the methods for wireless information transmission underwater.

Human knowledge and understanding of the world's oceans, which constitute the major part of our planet, rests on our ability to collect information from remote undersea locations. The major discoveries of the past decades, such as the remains of Titanic, or the hydro-thermal vents at bottom of deep ocean, were made using cabled submersibles. Although such systems remain indispensable if high-speed communication link is to exists between the remote end and the surface, it is natural to wonder what one could accomplish without the burden (and cost) of heavy cables. Hence the motivation, and our interest in wireless underwater communications. Together with sensor technology and vehicular technology, wireless communications will enable new applications ranging from environmental monitoring to gathering of oceanographic data, marine archaeology, and search and rescue missions.

The signals that are used to carry digital information through an underwater channel are not radio signals, as electro-magnetic waves propagate only over extremely short distances. Instead, acoustic waves are used, which can propagate over long distances. However, an underwater acoustic channel presents a communication system designer with many difficulties. The three distinguishing characteristics of this channel are frequency-dependent propagation loss, severe multipath, and low speed of sound propagation. None of these characteristics are nearly as pronounced in land-based radio channels, the fact that makes underwater wireless communication extremely difficult, and necessitates dedicated system design.

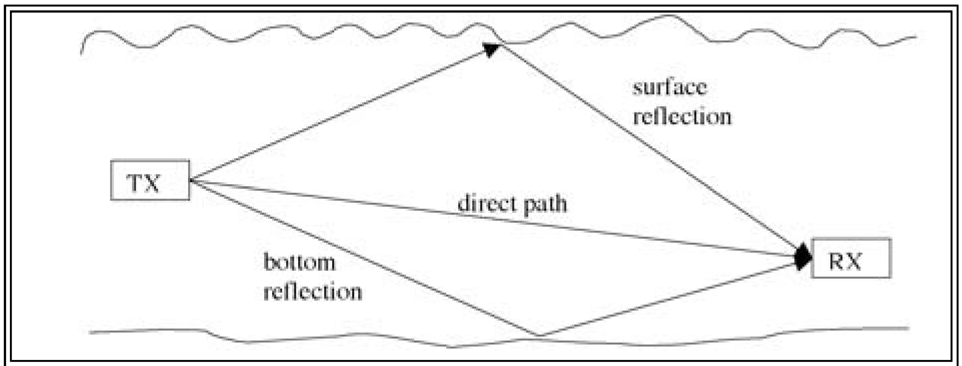

Fig. 1: Shallow water multipath propagation: in addition to the direct path, the signal propagates via reflections from the surface and bottom.

Path loss that occurs in an acoustic channel over a distance d is given as A=dka(f)d, where k is the path loss exponent whose value is usually between 1 and 2, and a(f) is the absorption factor that depends on the frequency f.. This dependence severely limits the available bandwidth: for example, at distances on the order of 100 km, the available bandwidth is only on the order of 1 kHz. At shorter distances, a larger bandwidth is available, but in practice it is limited by the that of the transducer. Also in contrast to the radio systems, an acoustic signal is rarely narrowband, i.e., its bandwidth is not negligible with respect to the center frequency.

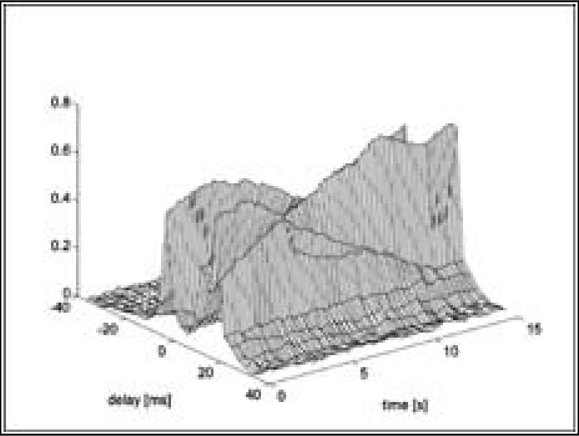

Fig. 2: Ensemble of channel impulse responses (magnitudes).

Within this limited bandwidth, the signal is subject to multipath propagation, which is particularly pronounced on horizontal channels. In shallow water, multipath occurs due to signal reflection from the surface and bottom, as illustrated in Figure 1. In deep water, it occurs due to ray bending, i.e. the tendency of acoustic waves to travel along the axis of lowest sound speed. Figure 2 shows an ensemble of channel responses obtained in deep water. The multipath spread, measured along the delay axis, is on the order of 10 ms in this example. The channel response varies in time, and also changes if the receiver moves. Regardless of its origin, multipath propagation creates signal echoes, resulting in intersymbol interference in a digital communication system. While in a cellular radio system multipath spans a few symbol intervals, in an underwater acoustic channel it can spans few tens, or even hundreds of symbol intervals! To avoid the intersymbol interference, a guard time, of length at least equal to the multipath spread, must be inserted between successively transmitted symbols. However, this will reduce the overall symbol rate, which is already limited by the system bandwidth. To maximize the symbol rate, a receiver must be designed to counteract very long intersymbol interference.

The speed of sound underwater varies with depth and also depends on the environment. Its nominal value is only 1500 m/s, and this fact has a twofold implication on the communication system design. First, it implies long signal delay, which severely reduces the efficiency of any communication protocol that is based on receiver feedback, or hand-shaking between the transmitter and receiver. The resulting latency is similar to that of a space communication system, although there it is a consequence of long distances traveled. Secondly, low speed of sound results in severe Doppler distortion in a mobile acoustic system. Namely, if the relative velocity between the transmitter and receiver is ±v, then a signal of frequency fc will be observed at the receiver as having frequency fc (1±v/c). At the same time, a waveform of duration T will be observed at the receiver as having duration T(1±v/c). Hence, Doppler shifting and spreading occur. For the velocity v on the order of few m/s, the factor v/c, which determines the severity of the Doppler distortion, can be several orders of magnitude greater than the one observed in a land-mobile radio system! To avoid this distortion, a noncoherent modulation/detection must be employed. Coherent modulation/detection

offers a far better utilization of bandwidth, but the receiver must be designed to deal with extreme Doppler distortion.
Summarizing the channel characteristics, one comes to the conclusion that an underwater acoustic link combines in itself the worst aspects of radio channels: poor quality of a land-mobile link, and high latency of a space link. In addition, current technology offers limited transducer bandwidth (typically a few kHz, or few tens of kHz in a wideband system), half-duplex operation, and limited power supply of battery-operated instruments.

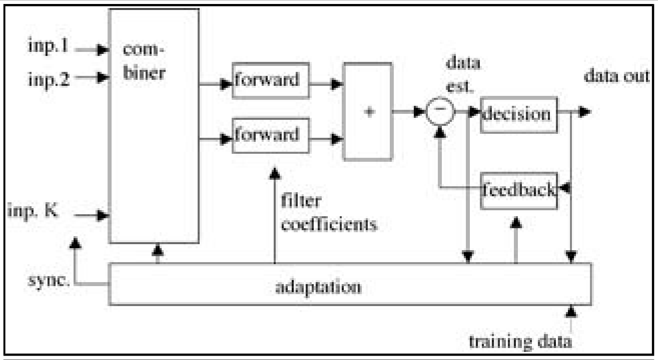

Fig. 3: Multichannel adaptive decision-feedback equalizer (DFE) is used for high-speed underwater acoustic communications. It supports any linear modulation format, such as M-ary PSK or M-ary QAM.

Acoustic modem technology today offers two types of modulation/detection: frequency shift keying (FSK) with noncoherent detection and phase-shift keying (PSK) with coherent detection. FSK has traditionally been used for robust acoustic communications at low bit rates (typically on the order of 100 bps). To achieve bandwidth efficiency, i.e. to transmit at a bit rate greater than the available bandwidth, the information must be encoded into the phase or the amplitude of the signal, as it is done in PSK or quadrature amplitude modulation (QAM). For example, in a 4-PSK system, the information bits (0 and 1) are mapped into one of four possible symbols, ±1±j. The symbol stream modulates the carrier, and the so-obtained signal is transmitted over the channel. To detect this type of signal on a multipath-distorted acoustic channel, a receiver must employ an equalizer whose task is to unravel the intersymbol interference. Since the channel response is not a-priori known (moreover, it is time-varying) the equalizer must "learn" the channel in order to invert its effect. A block diagram of an adaptive decision-feedback equalizer (DFE) is shown in Figure 3. In this configuration, multiple input signals, obtained from spatially diverse receiving hydrophones, can be used to enhance the system performance. The receiver parameters are optimized to minimize the mean squared error in the detected data stream. After the initial training period, during which a known symbol sequence is transmitted, the equalizer is adjusted adaptively, using the output symbol decisions. An integrated Doppler tracking algorithm enables the equalizer to operate in a mobile scenario. This receiver structure has been used on various types of acoustic channels. Current achievements include transmission at bit rates on the order of one kbps over long ranges (10-100 nautical miles) and several tens of kbps over short ranges (few km) as the highest rates reported to date. On a more unusual note, successful operation was also demonstrated over a basin scale (3000 km) at 10 bps, as well as over a short vertical channel at a bit rate in excess of 100 kbps. The multichannel DFE forms the basis of a high-speed acoustic modem implemented at the Woods Hole Oceanographic Institution. The modem, shown in Figure 4, is implemented in a fixed-point DSP, with a floating-point co-processor for high-rate mode of operation. When active, it consumes about 3 W in receiving mode, and 10-50 W to transmit. The board measures 1.75 _ 5 in, and accommodates four input channels. The modem has successfully been deployed in a number of trials, including autonomous underwater vehicle (AUV) communications at 5 kbps.

Fig. 4: The WHOI micro-modem has dual mode of operation: low rate FSK and high-rate PSK.

With advances in acoustic modem technology, sensor technology and vehicular technology, ocean engineering today is moving towards integration of these components into autonomous underwater networks. While current applications include supervisory control of individual AUVs, and telemetry of oceanographic data from bottom-mounted instruments, the vision of future is that of a "digital ocean" in which integrated networks of instruments, sensors, robots and vehicles will operate together in a variety of underwater environments. Examples of emerging applications include fleets of AUVs deployed on collaborative search missions, and ad hoc deployable sensor networks for environmental monitoring.

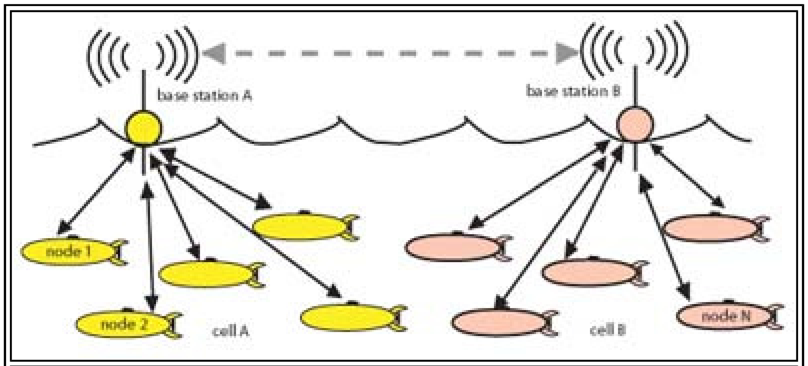

Fig. 5: Centralized network topology.

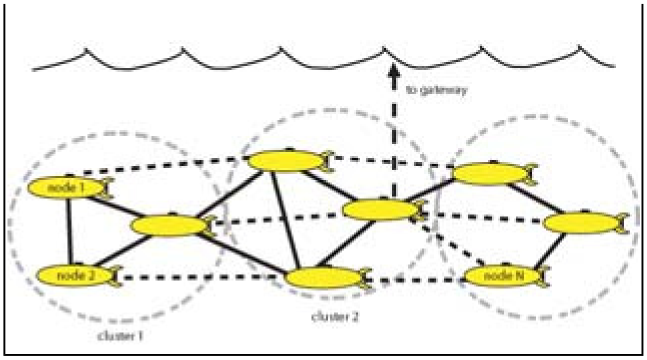

Fig. 6: Decentralized network topology.

Depending on the application, future underwater networks are likely to evolve in two directions: centralized and decentralized networks. The two types of topologies are illustrated in Figure 5 and Figure 6. In a centralized network, nodes communicate through a base station that covers one cell. Larger area is covered by more cells whose base stations are connected over a separate communications infrastructure. The base stations can be on the surface and communicate using radio links, as shown in the figure, or they can be on the bottom, connected by a cable. Alternatively, the base station can be movable as well. In a decentralized network, nodes communicate via peer-to-peer, multi-hop transmission of data packets. The packets must be relayed to reach the destination, and there may be a designated end node to a surface gateway. Nodes may also form clusters for a more efficient utilization of communication channel.

To accommodate multiple users within a selected network topology, the communication channel must be shared, i.e. access to the channel must be regulated. Methods for channel sharing are based on scheduling or on contention. Scheduling, or deterministic multiple-access, includes frequency, time and code-division multiple-access (FDMA, TDMA, CDMA) as well as a more elaborate technique of space-division multiple access (SDMA). Contention-based channel sharing does not rely on an a-priori division of channel resources; instead, all the nodes contend for the use of channel, i.e., they are allowed to transmit randomly at will, in the same frequency band and at the same time, but in doing so they must follow a protocol for medium-access control (MAC) to ensure that their information packets do not collide. All types of multiple-access are being considered for the underwater acoustic systems. Experimental systems today favor either polling, TDMA, or multiple-access collision avoidance (MACA) based on a hand-shaking contention procedure that requires an exchange of requests and clearances to send (RTS/CTS). Intelligent collision avoidance appears to be necessary in an underwater channel, where the simple principle of carrier sensing multiple access (CSMA) is severely compromised due to the long propagation delay—the fact that the channel is sensed as idle at some location does not guarantee that a data packet is not already in transmission at a remote location.

One of the major aspects of the evolving underwater networks is the requirement for scalability. A method for channel sharing is scalable if it is equally applicable to any number of nodes in a network of given density. For example, a pure TDMA scheme is not scalable, as it rapidly looses efficiency on an underwater channel due to the increase in maximal propagation delay with the area of coverage. In order to make this otherwise appealing scheme scalable, it can be used locally, and combined with another technique for spatial reuse of channel resources. The resulting scheme is both scalable and efficient; however, it may require a sophisticated dynamic network management. In contrast, contention-based channel allocation offers simplicity of implementation, but its efficiency is limited by the channel latency. Hence, there is no single best approach to the deployment of an underwater network. Instead, selection of communication algorithms and network protocols is driven by the particular system requirements and performance/complexity trade-offs.

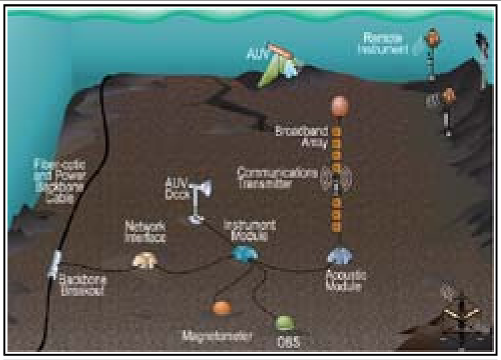

Fig. 7:A deep-sea observatory.

Research today is active on all topics in underwater communication networks: from fundamental capacity analyses to the design of practical network protocols on all layers of the network architecture (including medium access and data link control, routing, transport control and application layers) as well as cross-layer network optimization.

In addition to serving as stand-alone systems, underwater acoustic networks will find application in more complex, heterogeneous systems for ocean observation. Figure 7 shows the concept of a deep-sea observatory. At the core of this system is an underwater cable that hosts a multitude of sensors and instruments, and provides high-speed connection to the surface. A wireless network, integrated into the overall structure, will provide a mobile extension, thus extending the reach of observation.

While we have focused on acoustic wireless communications, it has to be noted that this will not be the only way of establishing wireless communication in the future underwater networks. Optical waves, and in particular those in the blue-green region, offer much higher throughput (Mbps) albeit over short distances (up to about 100 m). As such, they offer a wireless transmission capability that complements acoustic communication.

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