Underwater Acoustic Communication

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Synonyms
Underwater wireless acoustic communication, Underwater acoustic (UWA), Digital-to-analog (D/A), Analog-to-digital (A/D), Signal-to-noise ratio (SNR), Low earth orbiting (LEO), Frequency-shift keying (FSK), Orthogonal frequency-division multiplexing (OFDM), Intersymbol interference (ISI), Phase-shift keying (PSK), Quadrature amplitude modulation (QAM), Maximum likelihood sequence detection (MLSD), Spatial modulation (SM), Multiple input multiple output (MIMO), Maximum likelihood sequence estimation (MLSE), Space-time trellis codes (STTC), Layered space-time codes (LSTC), Single-input single-output (SISO), Trellis-coded modulation (TCM), Low-density parity check (LDPC)

Definition
Underwater acoustic (UWA) communication is a technique for sending and receiving messages by sound in water. As electromagnetic waves propagate poorly in sea water, acoustics provide the most obvious medium to enable underwater communications. UWA communication is difficult due to limited bandwidth, extended multipath, refractive properties of the medium, severe fading, rapid time variation, and large Doppler shifts. Compared to terrestrial communication, UWA communication has much lower data rates and shorter communication range.

Scientific Fundamentals

Basic System Model
A typical UWA communication system for the transmitter and receiver in the presence of UWA channels is shown in Fig. 1. Since acoustic signals have low frequency, the passband samples are often directly generated by the modulation module (Zhou and Wang 2014). After digital-to-analog (D/A) conversion, the passband signal is amplified, passed to matching circuits, and matched to the transducer. At the receiver side, the weak signal is increased in level by a preamplifier, filtered by a simple bandpass filter, and sampled at the passband. Finally, the bit information can be achieved by the demodulation module. From the signal processing point of view, the channel includes the imperfections of the transmitter and receiving circuits. All the modules that are lumped together are called channel...
between the D/A module and analog-to-digital (A/D) module.

**UWA Communication Channels**

UWA communication channels are generally recognized as one of the most difficult communication media in use today (Stojanovic and Preisig 2009). Acoustic propagation is best supported at low frequencies, and the bandwidth available for communication is extremely limited. Although the total communication bandwidth is very low, the system is, in fact, wideband, in the sense that bandwidth is not negligible with respect to the center frequency. Sound propagates in the water at a very low speed of approximately 1500 m/s, and propagation occurs over multiple paths. Delay spreading over tens or even hundreds of milliseconds results in frequency-selective signal distortion, while motion creates an extreme Doppler effect. All of these factors are the key problems to be solved in UWA communication. Next, we will introduce UWA communication channels from four aspects.

**Attenuation and Noise**

A distinguishing property of acoustic channels is the fact that path loss depends on the signal frequency. This dependence is a consequence of absorption (i.e., transfer of acoustic energy into heat). In addition to the absorption loss, the signal experiences a spreading loss, which increases with distance. The overall path loss is given by

\[ A(l, f) = \left( \frac{1}{l_r} \right)^k a(f)^{l-l_r}, \]

where \( f \) is the signal frequency and \( l \) is the transmission distance, taken in reference to some \( l_r \).

The path loss exponent \( k \) models the spreading loss, and its usual values are between 1 and 2 (for cylindrical and spherical spreading, respectively). The absorption coefficient is \( a(f) \), which can be obtained using empirical formula (Berkhovskikh and Lysanov 1982).

Noise in an acoustic channel consists of ambient noise and site-specific noise. Ambient noise is always present in the background of the quiet deep sea. Site-specific noise, on the contrary, exists only in certain places. For example, ice cracking in polar regions creates acoustic noise as do snapping shrimp in warmer waters. The ambient noise comes from sources such as turbulence, breaking waves, rain, and distant shipping. While this noise is often approximated as Gaussian, it is not white. Unlike ambient noise, site-specific noise often contains significant non-Gaussian components.

The attenuation, which grows with frequency, and the noise, whose spectrum decays with frequency, result in a signal-to-noise ratio (SNR) that varies over the signal bandwidth. If one defines a narrow band of frequencies of width \( \Delta f \) around some frequency \( f \), the SNR in this band can be expressed as

\[ \text{SNR}(l, f) = \frac{S_l(f)}{A(l, f)N(f)}, \]

where \( S_l(f) \) is the power spectral density of the transmitted signal. For any given distance, the narrowband SNR is thus a function of frequency.

Another important observation to be made is that the acoustic bandwidth is often on the order of the center frequency \( f_c \). This fact bears significant implications for the design of signal processing methods, as it prevents one from making the
narrowband assumption \((B \ll f_c)\) on which many radio communication principles are based. Respecting the wideband nature of the system is particularly important in multichannel (array) processing and synchronization for mobile acoustic systems.

All in all, the fact that the available bandwidth depending on the distance has important implications for the design of UWA networks. Specifically, it makes a strong case for multihopping, since dividing the total distance between a source and destination into multiple hops enables transmission at a higher bit rate over each (shorter) hop. The same fact helps to offset the delay penalty involved in relaying. Since multihopping also ensures lower total power consumption, its benefits are doubled from the viewpoint of energy-per-bit consumption on an acoustic channel.

Multipath
Multipath formation in the ocean is governed by two effects: sound reflection at the surface, bottom, and any objects and sound refraction in the water. The latter is a consequence of the spatial variability of sound speed. Sound speed depends on the temperature, salinity, and pressure, which vary with depth and location; and a ray of sound always bends toward the region of lower propagation speed, obeying Snell’s law. Near the surface, both the temperature and pressure are usually constant, as is the sound speed. In temperate climates, the temperature decreases as depth begin to increase, while the pressure increase is not enough to offset the effect on the sound speed. The sound speed thus decreases in the region called the main thermocline. After some depth, the temperature reaches a constant level of \(4 ^\circ C\), and from there on, the sound speed increases depth (pressure). When a source launches a beam of rays, each ray will follow a slightly different path, and a receiver placed at some distance will observe multiple signal arrivals. Note that a ray traveling over a longer path may do so at a higher speed, thus reaching the receiver before a direct stronger ray. This phenomenon results in a non-minimum phase channel response.

The impulse response of an acoustic channel is influenced by the geometry of the channel and its reflection and refraction properties, which determine the number of significant propagation paths, and their relative strengths and delays. Strictly speaking, there are infinitely many signal echoes, but those that have undergone multiple reflections and lost much of the energy can be discarded, leaving only a finite number of significant paths.

To put a channel model in perspective, let us denote by \(l_p\) the length of the \(p\)th propagation path, with \(p = 0\) corresponding to the first arrival. In shallow water, where sound speed can be taken as a constant \(c\), path lengths can be calculated using plane geometry, and path delays can be obtained as \(\tau_p = l_p/c\).

The surface reflection coefficient equals \(-1\) under ideal conditions, while bottom reflection coefficients depend on the type of bottom (hard, soft) and grazing angle (Jensen et al. 1994). If we denote by \(\Gamma_p\) the cumulative reflection coefficient along the \(p\)th propagation path, and by \(A(l_p, f)\) the propagation loss associated with this path, then

\[
H_p(f) = \frac{\Gamma_p}{\sqrt{A(l_p,f)}},
\]

represents the frequency response of the \(p\)th path. Hence, each path of an acoustic channel acts as a low-pass filter, which contributes to the overall impulse response,

\[
h(t) = \sum_p h_p(t - \tau_p),
\]

where \(h_p(t)\) is the inverse Fourier transform of \(H_p(f)\).

Time Variability
There are two sources of the channel’s time variability: inherent changes in the propagation medium and those that occur because of the transmitter/receiver motion. Inherent changes range from those that occur on very long timescales that do not affect the instantaneous level of a communication signal (e.g., monthly changes in temperature) to those that occur on short timescales and affect the signal. Prominent among the latter are changes induced by surface waves,
which effectively cause the displacement of the reflection point, resulting in both scattering of the signal and Doppler spreading due to the changing path length.

It is beyond the scope of the present treatment to summarize what is known about the statistical characterization of these apparently random changes in the channel response. Suffice it to say that unlike in a radio channel, where a number of models for both the probability distribution (e.g., Rayleigh fading) and the power spectral density of the fading process (e.g., the Jakes’ model) are well accepted and even standardized, there is no consensus on statistical characterization of acoustic communication channels. Experimental results suggest that some channels may just as well be characterized as deterministic, while others seem to exhibit Rice or Rayleigh fading (Chitre 2007). However, current research indicates K-distributed fading in other environments (Yang and Yang 2006). Channel coherence times below 100 ms have been observed (Preisig 2007) but not often. For a general-purpose design, one may consider coherence times on the order of hundreds of milliseconds. In the absence of good statistical models for simulation, experimental demonstration of candidate communication schemes remains a de facto standard.

The Doppler Effect

The motion of the transmitter or receiver contributes additionally to the changes in channel response. This occurs through the Doppler effect, which causes frequency shifting as well as additional frequency spreading. The magnitude of the Doppler effect is proportional to the ratio $a = \frac{v}{c}$ of the relative transmitter-receiver velocity to the speed of sound. Because the speed of sound is very low compared to the speed of electromagnetic waves, motion-induced Doppler distortion of an acoustic signal can be extreme. Autonomous underwater vehicles (AUVs) move at speeds on the order of a few meters per second, but even without intentional motion, underwater instruments are subject to drifting with waves, currents, and tides, which may occur at comparable velocities. In other words, there is always some motion present in the system, and a communication system has to be designed taking this fact into account. The only comparable situation in radio communications occurs in low Earth orbiting (LEO) satellite systems, where the relative velocity of satellites flying overhead is extremely high (the channel there, however, is not nearly as dispersive). The major implication of motion-induced distortion is on the design of synchronization and channel estimation algorithms.

The way in which these distortions affect signal detection depends on the actual value of factor $a$. For comparison, let us look at a highly mobile radio system. At 160 km/h (100 mph), we have $a = 1.5 \times 10^{-7}$. This value is low enough that Doppler spreading can be neglected. In other words, there is no need to account for it explicitly in symbol synchronization. The error made in doing so is only 1/1000 of a bit per 10,000 bits. In contrast to this situation, a stationary acoustic system may experience unintentional motion at 0.5 m/s (1 knot), which would account for $a = 3 \times 10^{-4}$. For an AUV moving at several meters per second (submarines can move at much greater velocities), factor $a$ will be on the order of $10^{-3}$, a value that cannot be ignored.

Non-negligible motion-induced Doppler shifting and spreading thus emerge as another major factor that distinguishes an acoustic channel from the mobile radio channel and dictates the need for explicit phase and delay synchronization in all but stationary systems. In multi-carrier systems, the Doppler effect creates particularly severe distortion. Unlike radio systems, in which time compression/dilation is negligible and the Doppler shift appears equal for all subcarriers, in an acoustic system each subcarrier may experience a markedly different Doppler shift, creating non-uniform Doppler distortion across the signal bandwidth.

Modulation Schemes

Incoherent Modulation

Most early UWA communications systems used incoherent modulation methods for reasons of simplicity and reliability (Chitre et al. 2008), such as binary frequency-shift keying (2FSK), whose modulation process is presented in Fig. 2.
Frequency-shift keying (FSK) is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier signal. However, there were a number of exceptions, in particular systems that were used in channels with little boundary action, for example, vertical links in deep water. Vertical links using directional transducers on unmanned underwater vehicles (UUVs) and ships are very clean, experiencing little or no delay spread, with the result that the biggest challenge is tracking the carrier phase that changes with respect to range.

Coherent Modulation
A typical coherent modulation process (binary phase-shift keying, 2PSK) is shown in Fig. 3. Binary phase-shift keying (2PSK) is a digital modulation process that conveys data by changing (modulating) the phase of a constant frequency reference signal (the carrier wave). Through the 1980s phase, coherent communication was used almost exclusively for deep water vertical links, but in the early 1990s phase, coherent communication in multipath channels began to attract attention, as incoherent methods were limited to a bandwidth efficiency of approximately 0.5 bits per Hz.

Single Carrier Modulation
One major step toward high rate communication is single carrier modulation of information symbols from constellations such as phase-shift keying (PSK) and quadrature amplitude modulation (QAM), whose block diagram is shown in Fig. 4 (Zhou and Wang 2014). With symbols $s[i]$ and pulse shaping filter $p(t)$, the transmitted signal is

$$x(t) = \sum_{i=-\infty}^{\infty} s[i]p(t - iT),$$

where $T$ is the symbol period. The corresponding passband signal can be obtained by

$$\tilde{x}(t) = 2 \text{Re} \left\{ x(t)e^{j2\pi f t} \right\}.$$

The channel introduces intersymbol interference (ISI) due to multipath propagation. When data symbols are transmitted at a high rate, the same physical channel leads to more channel taps in the discrete-time equivalent model. Advanced signal processing at the receiver side is used to suppress the interference; this process is termed channel equalization. Although widely used for slowly-varying multipath channels in radio applications, channel equalization for fast-varying UWA channel is a significant challenge.

Multi-carrier Modulation
Multi-carrier modulation offers an alternative to a broadband single carrier communication. By dividing the available bandwidth into a number of narrower bands, orthogonal frequency-division multiplexing (OFDM) systems can perform equalization in the frequency domain and eliminate the need for complex time-domain equalizers. The OFDM modulation process is described in Fig. 5. OFDM modulation and demodulation can easily be accomplished using fast Fourier transforms (FFT). A shallow water experiment in the Mediterranean Sea yielded good OFDM performance (BER $< 2 \times 10^{-3}$) at ranges by to 6 km (Frassati et al. 2005). At the same ranges, the DSSS performance was found to be significantly poorer.

OFDM systems often use a guard period (often implemented as a cyclic prefix or zero prefix) between consecutive OFDM symbols to avoid ISI. When the delay spread is long, the prefix length can significantly affect the bandwidth.
efficiency. Maximum likelihood sequence detection (MLSD) on individual subcarriers using a low complexity PSP can combat ISI when the symbol period is smaller than the delay spread (Morozov and Preisig 2006). Other channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency.

When using coded OFDM, consecutive symbols are often striped across subcarriers to reduce the error correlation due to fading. However, impulse noise present in some environments can affect multiple subcarriers simultaneously and hence generate correlated errors. The use of a channel interleaver with coded OFDM allows symbols to be distributed over frequency-time plane, thus allowing the code to make maximal use of frequency and time diversity offered by OFDM (Chitre et al. 2005). The knowledge of error correlation due to impulsive noise could be used in future decoding algorithms to improve decoding performance.

OFDM systems are very sensitive to the Doppler shift due to the small bandwidth of each subcarrier as compared to the Doppler shift. As the carrier frequency in UWA systems is typically low as compared to the Doppler shift experienced due to movement, the communication systems have to cope with wideband Doppler which results in non-uniform Doppler shift across subcarriers. In Stojanovic (2006), the author presents an algorithm for non-uniform Doppler compensation in OFDM systems based on a single adaptively estimated parameter. In Sharif et al. (2000), the authors present a preprocessor that estimates Doppler shift by measuring the time between two known signals and removes the Doppler shift using a computationally efficient linear interpolator. Being a preprocessor, the technique can be used with any type of modulation and equalization.

Spatial Modulation

The process of spatial modulation (SM) is shown in Fig. 6. Information theoretic studies have shown that the capacity of a channel increases linearly with the minimum of the number of transmit and receive antennas. This increase in capacity translates to a corresponding increase in achievable data rate through the use of multiple input multiple output (MIMO) processing techniques and space-time coding.

Optimal detection techniques such as MAP and maximum likelihood sequence estimation (MLSE) exponentially grow in terms of complexity with the number of antennas. To address this problem, space-time trellis codes (STTC) and layered space-time codes (LSTC) can be used with suboptimal decoding techniques (Roy et al. 2004). The benefits of MIMO over single-input

Underwater Acoustic Communication, Fig. 3  Coherent modulation (2PSK)

Underwater Acoustic Communication, Fig. 4  Single carrier modulation

Underwater Acoustic Communication, Fig. 5  Multi-carrier modulation
single-output (SISO) UWA communication systems were successfully demonstrated through an experiment in the Mediterranean Sea using two transmit projectors for STTC and four transmit projectors for LSTC. In another set of experiments with six transmit projectors, a spatial modulation scheme with an outer block code, interleaver, and an inner trellis-coded modulation (TCM) was demonstrated (Kilfoyle et al. 2005). The experiments demonstrated that the proposed spatial modulation scheme offered increased bandwidth and power efficiency as compared to signals constrained to temporal modulation. For ISI-limited channels, spatial modulation offers the possibility of increasing data rates when simply increasing transmission power does not. In a MIMO-OFDM experiment, the nearly error-free performance was achieved with a 2-transmitter 4-receiver setup at ranges up to 1.5 km using a ½-rate low-density parity check (LDPC) code at a coded data rate of 12 kbps (Li et al. 2007).

Key Applications

As efficient communication systems are developing, the scope of their applications continues to grow, and so do the requirements on the system performance (Stojanovic 1999). Many of the developing applications, both commercial and military, are calling for real-time communication with submarines and AUVs, UUVs. Setting the underwater vehicles free from cables will enable them to move freely and refine their range of operation. The emerging communication scenario in which the modern UWA systems will operate is that of an underwater data network consisting of both stationary and mobile nodes. This network is envisaged to provide an exchange of data, such as control, telemetry, and eventually video signals, between many network nodes. The network nodes, located on underwater moorings, robots, and vehicles, will be equipped with various sensors, sonars, and video cameras. A remote user will be able to access the network via a radio link to a central node based on a surface station. Moreover, UWA communication plays a crucial role in the frogman information system. Compared with other communication forms such as electromagnetic waves, UWA communication has a longer operating range and more reliable performance.

Cross-References

▶ Electromagnetic Waves Communication
▶ Underwater Acoustic Communication
▶ Underwater Communication

References

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