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Impact of the Underwater Acoustic Channel on the Design of Digital Underwater Acoustic Communication Systems

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ABSTRACT

Digital underwater acoustic communications (UW Comms) systems have found increasing attraction for various applications that demand wireless data exchange. An UW Comms data link needs to cope with the challenges posed by the underwater acoustic channel, while simultaneously addressing various operational demands that are required by the intended application scenario. This paper provides a tutorial insight into design aspects and technical options for setting up operational UW Comms systems.

Keywords: *digital underwater acoustic communications, underwater acoustic channel, UW Comms system design.*

1. INTRODUCTION

Utilizing sound as the information bearer, digital underwater acoustic communications (UW Comms) systems allow for a wireless exchange of information over distances up to several tens of kilometers underwater. Unlike analog voice communication, digital acoustic links allow direct machine-to-machine data communication.

While the development of UW Comms systems was originally motivated by military demands [1], digital acoustic links found increasing attraction also for various civil applications, and enabled new types of operations in the underwater domain. Examples are tactical links to and from submerged military platforms, data exchange in sensor networks for monitoring environmental conditions, as well as command and control of unmanned vehicles operating in off-shore operations. The comms scenario can be a simple broadcast of information to multiple users or a point-to-point link between two single users. The latter case can further be expanded to a network of communication nodes, where messages can be routed to specific users with a unique address.

UW Comms systems are challenged by the underwater acoustic channel that significantly differs from the conditions encountered in radio frequency communications (RF Comms) in air. The influence of the underwater medium needs to be carefully considered for the design of UW Comms systems and networks.

Although digital underwater telemetry systems have been of interest since decades [2]-[4], the field of UW Comms has been systematically advanced since the 1990's. Various research projects investigated the applicability of waveforms, appropriate receiver structures, as well as networking aspects, e.g. [5]-[9]. Summaries of the impact of the underwater acoustic channel on UW Comms signals have been compiled and can e.g. be found in [10]. Based on the scientific results, a variety of commercial UW Comms products have been developed, culminating into todays state-of-the-art software-defined modems [11]. However, all technical solutions are in general driven by different underlying design considerations. Therefore, the commercial modems summarized in [11] differ in their respective supported frequency band, utilized modulation scheme, employed transmit power, as well as achieved data rate and communication range.

Aim of this paper is to provide a tutorial insight into design aspects and options for setting up operational digital UW Comms systems. The paper is organized as follows. Section 2 reviews the properties of the underwater acoustic channel that are most relevant for UW Comms links. Section 3

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summarizes the resulting impact on digital comms signals. Based on this, aspects for UW Comms system design are provided in Section 4. An outlook to standardization issues is given in Section 5. Finally, Section 6 concludes the paper.

2. UNDERWATER ACOUSTIC CHANNEL

The fundamentals of underwater acoustics are thoroughly addressed in literature e.g. [12]-[14]. In the following, the effects of an underwater acoustic channel are summarized that are of most importance for UW Comms.

2.1 Propagation of Sound

The *speed of sound* in water c_w is in the order of 1500 m/s and depends on temperature, salinity, and pressure, which in general vary with depth [12]-[14]. The resulting function of c_w over depth is called sound speed profile (SSP) which defines the spreading conditions in water, since sound waves are refracted towards regions of slower speed of sound. In case of a non-constant SSP, sound in water does not follow a straight line spreading. As a consequence, acoustic convergence zones as well as acoustic shadow zones are formed, where the latter will never be reached by acoustic energy. Figure 1 shows a simulated sound pressure distribution over depth and horizontal range assuming the SSP shown within the Figure. The acoustic source is placed at 25 m depth transmitting a mono-frequent signal of 1 kHz. The red dashed ellipsoid marks an acoustic shadow zone in 12 m depth at a distance of less than 500 m from the source.

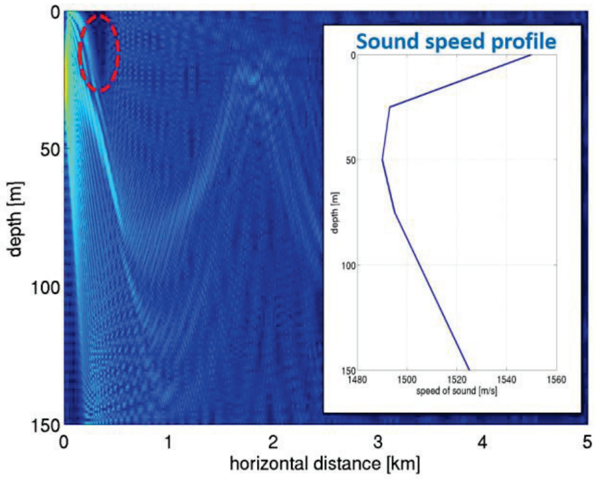

Figure 1. Simulated sound pressure distribution (color code: *dark blue* to *red* = *low pressure level* to *high pressure level*).

The natural bounds of the underwater acoustic channel are the sea surface and the sea bottom. Both boundaries reflect and scatter sound waves. A non-stationary sea surface can introduce Doppler, while parts of acoustic energy can be absorbed by the bottom.

2.2 Attenuation

Acoustic waves propagating through the underwater medium encounter different kinds of losses.
First, geometrical spreading cause the emitted energy to be spread over a surface that is increasing with radial distance d to the acoustic source [14]. In the simple case of spherical spreading the acoustic intensity is decreasing with d^{-2}. For shallow water environments, waves follow a rather cylindrical spreading where intensity drops with just d^{-1}.
Furthermore and most important, acoustic energy is absorbed by sea water due to viscosity and relaxation of molecules [12]-[14]. This kind of loss increases with frequency f where the attenuation in dB/km can be modelled as

$$\alpha = c_1 \frac{f_1 f^2}{f_1^2 + f^2} + c_2 \frac{f_2 f^2}{f_2^2 + f^2} + c_3 f^2 . \qquad (1)$$

Coefficients f_1 and f_2 denote the relaxation frequencies, while c_1, c_2, and c_3 depend on temperature, pressure, and salinity [14]. Figure 2 shows the attenuation due to absorption in dependence on frequency for typical values of the coefficients in Eqn. (1), yielding α =1 dB/km for f=10 kHz.

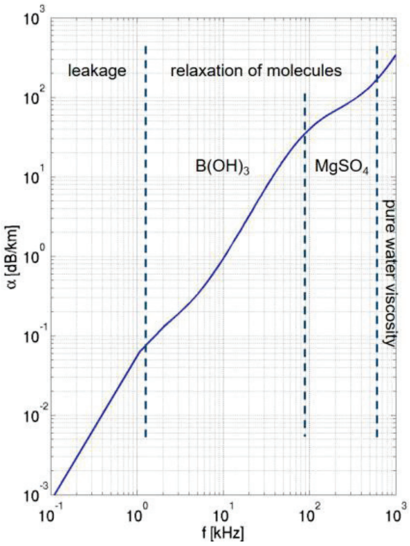

Figure 2. Attenuation due to absorption in [dB/km] vs. frequency.

2.3 Noise

The underwater soundscape is characterized by a variety of different noise sources that differ in origin and respective characteristics [12], [14], [16], [17].

2.3.1 Man made noise

Shipping noise is composed of two main sources: first, the sounds and vibrations emitted by a ship's machinery and auxiliary systems (e.g. pumps, gears, etc.) yield distinct narrowband lines in the frequency band between a few 10's of Hz up to a few 100's of Hz. Furthermore, cavitation at the blades of a ship's propellers generates air bubbles, which cause a broadband noise when collapsing. The covered frequency band ranges from a few 10's of Hz up to a few kHz with the main spectral contributions being in the frequency region roughly below 100 Hz. Above 100 Hz, the shipping noise level decreases with frequency f by roughly $-20\log f$ (i.e. 6 dB per octave) [12], [14].

Active sonar systems emit acoustic energy into the water and evaluate the received echoes for different kind of applications. Sonars for hunting submarines are characterized by high source levels and can employ narrowband pulses as well as broadband pulses, all of which in the frequency band between 1 kHz up to about 10 kHz. Navigational systems like Doppler log sonars or obstacle avoidance sonars operate between a few 10's of kHz up to 1 MHz. Imaging sonars operate between 100 kHz up to several 100's of kHz, employing broadband pulses.

2.3.2 Biological noise

Zoological inhabitants of the sea can generate different kind of sounds. Marine mammals utilize hydroacoustic signals for communications as well as for echo location purposes. The employed waveforms can be of narrowband or broadband nature, and can range from just a few Hz up to some 100 kHz. The achieved sound levels are sometimes comparable to powerful active sonar systems. Another example are snapping shrimps that can be found in warm shallow water regions [14], [18]. These animals use their claw to create cavitation bubbles, where the implosion of the bubbles generates a broadband noise. The main spectral contributions occur above 1 kHz [14], where the loudness of a snapping shrimp chorus typically ranges from 173 dB re 1µPa @ 1 m to 183 dB re 1µPa @ 1 m in the frequency band between 2 kHz and 300 kHz [19]. Due to the impulsive characteristic of the snapping noise, the statistic of the amplitude distribution is not Gaussian, but can be modelled by a symmetric alpha-stable distribution [20].

2.3.3 Environmental noise

Atmospheric interactions with the sea surface are the dominant source for permanent ambient noise in the underwater domain [16], [17]. Wind can cause breaking waves and induces microbubbles in the upper layer. When imploding, these bubbles generate broadband noise between a few Hz up to a few 10's of kHz. The quantitative impact of this noise is correlated with the underlying sea state. Furthermore, rain on the sea surface cause broadband noise, too, which mainly covers the frequency band between 1 kHz and 100 kHz, and exhibiting a maximum level at about 20 kHz [14].

3. IMPACT OF UNDERWATER ACOUSTIC CHANNEL ON UW COMMS SYSTEMS

In the following, the most important influences on UW Comms systems are derived from the effects described Section 2.

3.1 Availability of data service

As described in Section 2.1, the sound propagation conditions in the underwater acoustic channel can cause acoustic shadow zones, where an emitted UW Comms signal cannot be received at all. This problem can only be overcome if transmitter and/or receiver change their respective position/depth until a connection can be established. Alternatively, the receiver could be equipped with multiple sensors that vertically sample the water column. However, the latter solution comes at the cost of increased receiver complexity and is not applicable for every scenario.

In any case, operators of UW Comms systems must at least be aware of the fact that situations are possible, where an UW Comms link cannot be established.

3.2 Range dependent limited data rate

The acoustic losses summarized in Section 2.2 require in general a transmitter with sufficiently high power. Due to the frequency dependent attenuation, the applicable center frequency of an UW Comms signal decreases with increasing distance from the emitting source. Table 1 provides examples of applicable center frequencies f_c for different transmission distances d.

Table 1. Applicable center frequency f_c for transmission distance d.

Transmission distance [km]	Center frequency [kHz]
$100 < d \leq 1000$	$f_c < 1$
$1 < d \leq 10$	$f_c \sim 10$
$d \leq 0{,}1$	$f_c > 100$

The corresponding exploitable bandwidth is roughly in the order of the respective center frequency [10], and will be about 10 kHz and less for distances over several kilomters.
Since the maximum achievable data rate of a digital communication system depends on the available bandwidth, the data throughput of UW Comms systems is coupled to the desired maximum transmission distance. More detailed theoretical considerations can be found in [15].
Furthermore, data rates are quite limited. The particular value depends on the utilized modulation scheme, but ranges roughly from a few bit/s for long-range UW Comms over ranges of tens of kilometers, up to some 100 kbit/s for transmission distances less than 100 m.

3.3 Spread of comms signals in time

Due to refraction caused by the underwater medium as well as reflections at its boundaries, sound waves can travel via different paths through the water layer, where each path is associated with an individual travel time. As a consequence of such multipath spreading, differently delayed copies of an UW Comms signal overlap in time and interfere with each other at a certain receiver position.
Depending on the channel the delay spread can range from a few milliseconds to 100's of ms. This causees multiple subsequently transmitted information symbols to interfere, known as intersymbol interference (ISI) which needs to be countered by a proper receiver processing and/or smart waveform design. Note, that each spreading path exhibits a unique vertical angle of arrival at a receiver position which might be exploited if an vertical array is used for reception.

3.4 Spread in frequency and temporal scaling of comms signals

Relative motion between an UW Comms transmitter and a receiver changes the distance and, hence, the travel time between the two assets during the propagation of an information bearing acoustic wave. The impact on the received signal is the well known Doppler effect, which causes a frequency shift as well as a temporal scaling of the originally transmitted signal. Both signal distortions quantitatively depend on the particular speed of the relative velocity, the speed of sound, and the center frequency of the comms signal.
This can be shown for the exemplary case of a linear relative motion between a transmitter and receiver. In this case, the travel time τ between the two assets changes with time t according to

$$\tau(t) = \frac{v_{\mathrm{rel}} t + d_0}{c_{\mathrm{w}}}, \tag{2}$$

where v_{rel} denotes the relative speed, and d_0 is the initial distance at $t = 0$. Having $s(t)$ as the originally transmitted signal and neglecting all channel effects except the linear motion, the received signal is given by

$$r(t) = s\big(t - \tau(t)\big) = s(\gamma t - \tau_0), \tag{3}$$

where $\gamma = 1 - v_{\mathrm{rel}}/c_{\mathrm{w}}$ and $\tau_0 = d_0/c_{\mathrm{w}}$. It can be shown that the temporal scaling γ causes $s(t)$ also to be shifted in frequency by

$$f_{\mathrm{D}} = \frac{v_{\mathrm{rel}}}{c_{\mathrm{w}}} f_c, \tag{4}$$

where f_c denotes the center frequency of $s(t)$.

For c_{w}=1500 m/s, v_{rel} = 3 m/s and f_c=8 kHz, the resulting Doppler shift of f_{D}=16 Hz seems somewhat mild. However, the scaling factor becomes γ=0,998, such that the time bases of $s(t)$ and $r(t)$, respectively, are already 2 ms apart after only 1 s. This drift would correspond to a duration of two symbols if the UW Comms system operates with a baud rate of 1000 symbols/s second.
Therefore, not only a proper carrier frequency synchronization is required but also the temporal scaling due to Doppler must be properly addressed by the processing on the receiver side.

3.5 Interfering noise

As summarized in Section 2.3, the underwater acoustic medium is characterized by noise from various sources that interfere with UW comms signals.
On the receiver side the signal of interest must first be detected in the received noisy hydroacoustic signal, and then subsequently be extracted. The required processing steps need to take into account the statistical properties of the noise disturbances and might exploit the spatial distribution of the noise sources.

4. UW COMMS SYSTEM DESIGN

Core of an UW Comms system is the employed acoustic waveform for transmitting digital information, known as the physical layer (PHY). It needs to cope with the challenges posed by the underwater acoustic channel summarized in Section 3, and determines the system's hardware components as well as the signal processing steps required on receiver side. The design of the PHY is particularly driven by the operational demands of the intended application scenario. Figure 3 shows the impact of the desired communication range, the required information update rate, and the information content on the major technical requirements of an UW Comms link.

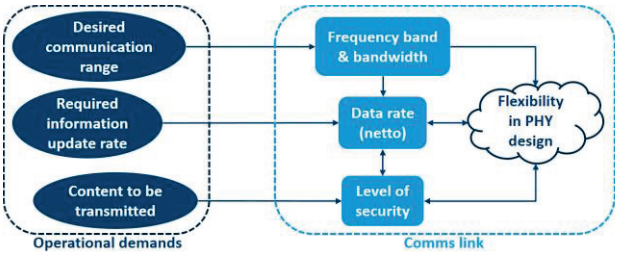

Figure 3. Impact of operational demands on comms link design.

The desired maximum communication distance determines the frequency band available for an UW Comms link. This limits the maximum realizable data rate which is also driven by the demanded information update rate. Finally, the type of information to be transmitted rules the required level of security. An UW Comms link might either be unprotected or can be secured on the PHY level (transmission security, TRANSEC) and/or on the message content level (communication security, COMSEC). While TRANSEC has direct impact on the waveform solution, COMSEC can be realized independent of the PHY by applying means of crypto to the data content. This can increase the total length of a data message, thus affecting the netto data rate.

The resulting technical requirements put the constraints on the particular design of the PHY.

4.1 PHY related aspects

Basic ideas of PHY solutions known from digital communications theory [21] can likewise be applied to digital underwater acoustic communication. The modulation methods can in general be grouped in incoherent approaches and coherent approaches.

Incoherent modulation schemes encode the information in the transmit signal's amplitude and/or frequency only. A well known example is frequency shift keying (FSK) that maps bits to certain frequency lines in the spectrum. The processing required for such methods is typically of low complexity. Due to the signal's simplicity, incoherent modulation schemes are well suited to support less sophisticated hardware components on transmitter and receiver side. However, these approaches make an inefficient use of the available bandwidth and cannot achieve high data rates for a given channel.

Coherent modulation schemes do also employ the communication signal's phase to encode information. One basic example is binary phase shift keying (2-PSK) where the amplitude of the communication signal remains constant, while the 0 bit is mapped to a phase of 0 and the 1 bit is assigned to a phase value of π. This principle is generalized in M-PSK where a set of M phase symbols is considered for encoding groups of bits. Quadrature amplitude modulation (QAM) as another example encodes information by using amplitude and phase of a signal. Coherent PHY solutions allow for the most efficient use of the available bandwidth and are therefore of interest for UW Comms applications that demand higher data rates. However, this advantage comes at the cost of increased processing complexity and higher computational load, since coherent approaches require an accurate recovery of the employed carrier frequencies as well as sufficient recovery of the underlying timing grid. Furthermore, equalization for countering ISI and compensation of residual phase-offsets are crucial.

For the choice of the PHY, the characteristics of the expected underwater noise are crucial. For example, FSK-type modulation schemes are vulnerable to narrowband interferences that occur in the frequency band of the UW Comms signal.

In the following subsections 4.1.1 - 4.1.3 some approaches on PHY level are exemplarily summarized that increase the robustness and/or introduce some degree of security of an UW Comms systems. Note that neither of the techniques will increase the maximum possible data rate which is purely limited by the available bandwidth of the underwater acoustic channel.

4.1.1 Differential PSK

In PSK schemes the information is encoded in the absolute value of the comms signal's phase. Although a receiver should properly synchronize to the carrier frequency, a remaining small frequency offset will always be present in reality. This causes the processed signal's phase to drift in time, leading to errors in the decoded bit stream if not properly catched. *Differential PSK* encodes the information in the phase difference between two subsequent data symbols. Assuming that the receiver's phase drift is similar for subsequent data symbols, the phase difference is approximately preserved. This improves the robustness of the system with respect to carrier frequency synchronization errors.

4.1.2 Orthogonal Frequency-Division Multiplexing

Multi-carrier approaches like the orthogonal frequency-division multiplexing (OFDM) have also found their way into the UW Comms domain. In OFDM, a data stream is split up into m subdata streams, which are then transmitted in parallel by employing single carrier modulation in m orthogonal frequency bands. Typically, PSK-type modulation is employed for transmitting the subdata packets in their respective frequency band. The effective data rate of an OFDM system is m times the data rate of a single subchannel. This allows to operate with low data rates in the subchannels, which are thus less affected by multipath induced ISI. Since the subdata packets are transmitted via orthogonal frequency bands, errors in one subchannel will not affect the other subchannels, which increases the robustness of the data link. Besides the technical challenges posed by the employed single carrier modulation, OFDM requires good carrier synchronization to avoid interchannel crosstalk.

4.1.3 Spread Spectrum Approaches

Coherent as well as incoherent waveforms can be combined with *spread spectrum approaches*. The resulting spread spectrum comms signals are characterized by a spectral bandwidth that is much greater than it would be required for realizing the intended data rate [21].

Synthetically scaling a comms signal to a larger bandwidth can counter or even avoid the influence from interfering sources like e.g. narrowband noise, thus increasing the robustness of the comms link. Furthermore, when spread in frequency domain, comms signals can be transmitted at lower power levels. This reduces the probability of detection in the presence of noise providing a TRANSEC feature to the PHY. Code division multiple access (CDMA) use the spread spectrum approach to encode a waveform with a unique individual spreading code. Only receivers with knowledge of the respective spreading key can recover the originally transmitted waveform. This introduces further security and allows a channel to be used by multiple users at the same time.

An example for spreading of a coherent waveform is *direct sequence spread spectrum* (DSSS). In DSSS the message bits are modulated by a pseudorandom bit sequence. The sequence bits are called chips and are of shorter duration than the original information bearing bits which results in a correspondingly larger bandwidth of the spread signal.

Frequency hopping (FH) is another simple form of spread spectrum which is applied in conjunction with incoherent waveforms. FH changes the carrier frequency with time e.g. for each single data symbol. This allows to reduce the effect of ISI due to multipath, and to increase the robustness against narrowband interferers. It furthermore offers some degree of TRANSEC if the hopping sequence remains undisclosed. Note that FH is not well suited for coherent modulation schemes since the signal's phase is disturbed by each frequency hop.

4.2 Receiver processing related aspects

Task of the signal processing on the receiver side is to recover the original transmitted information. Although the particular receiver structure and implemented processing depend on the utilized PHY solution, some steps like signal detection, carrier frequency synchronization, and timing synchronization are required by all UW Comms systems. The receiver processing must be able to adapt to time-varying conditions since the underwater acoustic channel can and will change in space and time, even during the transmission of a comms signal. The complexity and performance of a receiver implementation is directly coupled with the employed wet-end hardware as well as the available processing platform. Multichannel receivers for example allow spatial processing for suppression of localized noise sources and incoming multipaths, and for resolving different UW Comms user. However, the corresponding receiver implementation requires powerful processing platforms.

4.3 Hardware related aspects

The employed wet-end hardware needs to support the demands of the PHY. In particular, the transfer functions of the utilized amplifiers and transducers on the transmitter side as well as hydrophones and amplifiers on the receiver side need to support the desired frequency bands. In case of coherent UW Comms waveform, the hardware components must not destroy phase information.

Computational performance of the available processing platform limits the complexity of the receiver structure and the processing steps. The choice of the particular processing platform is driven by the demands and capabilities of the overall system that hosts the UW Comms system.

For example, in small unmanned underwater vehicles (UUV's) space and energy are limited. Therefore, UW Comms modems installed on UUV's typically employ single channel wet-ends and rely on small processing platforms with low energy consumption and limited computational power.

In contrast to this, a passive sonar system of a submarine is a high-sophisticated UW Comms receiver hardware platform [22]. The subs different sonar arrays can receive UW Comms signals in different frequency bands. In particular, the arrays offer a high signal gain and are able to spatially resolve UW Comms signals that imping under different bearings. Furthermore, the processing power of the sonar system provides sufficient computational performance to support the detection and decoding of multiple PHY solutions.

4.4 Verification of UW Comms system designs

For evaluating an UW Comms system design, the PHY solution as well the implemented receiver processing can be tested using benchmark tools like [23] where underwater acoustic channels can be simulated or replayed. Such simulation-based analysis should be performed before testing a new system design in expensive sea trials.

5. STANDARIZATION OF PHY SOLUTIONS

Commercially available systems often employ proprietary PHY solutions of the respective manufacturer, such that only systems of the same kind can exchange data. In order to ensure interoperability between different kinds of modems, communication standards are required.

For the development of standards, the limitations of the available different modem hardware need to be considered. The resulting solution is a good compromise that fits many hardware platforms, but is not necessarily optimal for specific systems.

Standards already address the challenges of the underwater acoustic channel to a certain degree, and might furthermore cover security measures to protect UW Comms links [24]. Therefore, the support of suitable standards should be carefully considered when designing an UW Comms system which helps to lower technical risks and costs of the system development.

A well-known example for standardization efforts is the JANUS protocol. It is the first world-wide standard for UW Comms which has been openly defined by NATO [25] and employs an FH FSK modulation scheme. Although this approach does not efficiently use the available bandwidth, it allows for robust low data rate communications and supports existing legacy hardware that is already available on different underwater assets. Different kind of applications for JANUS have been proposed and successfully tested in field trials [25].

Since different underwater missions pose different requirements on UW Comms links, it is unlikely that there will ever be a one-fits-all PHY. The appearance of different standards can rather be expected, where each technical solution is optimized for a certain set of operational demands.

6. SUMMARY

Digital underwater acoustic communication enables wireless data exchange underwater over distances of operational interest. UW Comms links are faced by a demanding transmission medium that cause severe spread of comms signals in time and frequency domain, and which is affected by different noise sources of broadband and narrowband nature. Furthermore, the availability of data service cannot be guaranteed for every transmitter-receiver geometry, while the achievable data rate channel is limited and dependent on range. All effects need to be carefully considered when designing an UW Comms system. Modulation methods known from digital wireless RF Comms are in principle applicable, but need to be adapted to the special conditions of the underwater acoustic channel. The choice of the PHY is driven by the operational demands, while its design depends on the available hardware solutions. UW Comms standards enable interoperability between systems of different manufacturers, and can limit risks and costs of a modem development.

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