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Low Probability of Detection for Underwater Acoustic Communication: A Review

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***Abstract*—Low probability of detection (LPD) is an extremely important characteristic of an underwater acoustic communication (UWAC) system when used for military-related applications, since the detection of a communication signal in the channel may reveal the presence of the transmitter or receiver. Furthermore, the recent advances in the understanding of the environmental effects of sound transmission in the ocean has led to a growing interest in LPD for UWAC also for civilian use. This is because systems that are designed for reliable communication at low signal power have a reduced environmental impact. In this paper, we identify the main challenges for the design of UWAC LPD systems. We describe and classify common approaches for transmission, reception, and interception of LPD signals, and we discuss their advantages and weaknesses. We also present several methods to determine the LPD capability of a system and suggest to adopt the range ratio test as a performance measure that captures the effects of signal propagation through the UWAC channel and the capabilities of the communication receiver and a signal interceptor. In light of the environmental benefits of LPD transmission and ongoing discussions about limiting the power spectral density of UWAC signals through regulations, we believe that LPD transmission is an area of growing importance for UWAC research and development. We hope that this paper serves as a motivation and a starting point for further research in this field.**

***Index Terms*—Underwater acoustic communication, Low probability of detection, Sound detection, Covert communication, Interception, Secure underwater acoustic communication**

I. INTRODUCTION

In this paper, we survey the current approaches for low probability of detection (LPD) systems for underwater acoustic communication (UWAC). LPD is required in many applications of data communications over electromagnetic (EM) and acoustic channels. While there are many similarities for LPD over different channels, the harsh underwater acoustic environment presents some extreme challenges for LPD communications. We attempt to highlight these challenges as well as the means that have been applied to overcome them.

A. Applications for LPD UWAC

UWAC is an enabling technology for various applications, such as retrieving sensor data for ecosystem monitoring, exploring natural resources from the ocean, or providing navigation aid and command and control capabilities [1]. Also military surveillance systems use UWAC, for example when mobile devices such as autonomous underwater vehicles (AUVs), drifters such as gliders and underwater buoys, and human divers require either peer-to-peer or network communication capability for threat detection and long range survey. While covert transmission is also required for active sonar activities for estimating the range to an object without being detected [2], the majority of applications for low probability of detection (LPD) involves underwater acoustic communications. For military applications, LPD is of interest when the transmitter (e.g., a submarine) wishes to remain undetected, or when the mere knowledge of communication may point to the existence of a receiver (e.g., a diver). As such, in LPD communication only the detection capability of an interceptor is considered, i.e., an interceptor need not be able to actually decode the communication signal[1] [3]. A summary of the need for secure underwater acoustic communication is given in [4].

Besides supporting military applications, the notion of LPD also helps to reduce the environmental impact of acoustic communication. Man-made acoustic activities can greatly affect marine animals such as marine mammals [5]. As illustrated in Fig. 1, the sound produced by marine animals is in frequency bands used also by most underwater acoustic modems [6]. Hence, the activity of UWAC modems can directly impact the communication means of these animals and thus their natural behavior. Since LPD communication aims towards transmission with low power spectral density and eventually with low power, it reduces the level of interference with marine-life communication [7]. Moreover, UWAC may cause health problems to marine animals through exposure to high power signals. Studies have shown that both the source level and spectral content of the signals have an effect on the body [8].

Reducing the sound level though LPD communications therefore has also an environmental merit. In fact, experimental results proved that regardless of the duration of exposure to sound, the accumulated affect is negligible when the pressure level is low [9]. Similarly, LPD helps to reduce the effect of acoustic sound on human divers carrying or operating close to underwater acoustic modems. Studies have shown that acoustic sound of high power spectral density can cause irreparable damages to a diver's hearing and even the backbone [10]. For this reason, health regulations adapted from airborne acoustic studies limit the level of per-Hz acoustic sound transmitted in the immediate surrounding of a diver [11]. The growing knowledge of the effects of underwater sound has

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[1] LPD is sometimes confused with low probability of intercept (LPI), where an eavesdropper is interested in actually decoding an intercepted packet.

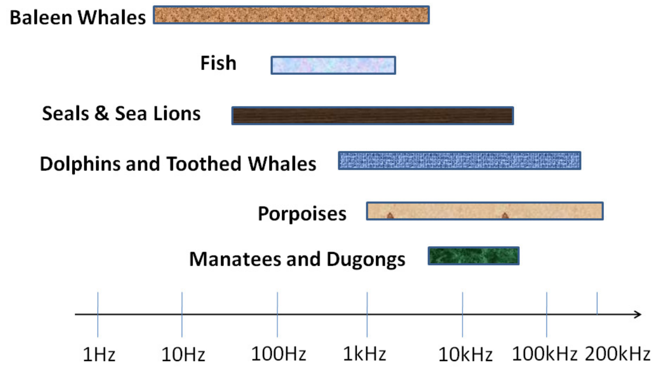

Fig. 1: Frequency range of sound produced by marine animals. Figure courtesy of B. Southall.

also motivated efforts to generally limit sound transmission in the ocean through regulations, and new standards are expected in the near future [12], [13]. For example, Ocean Networks Canada (ONC) aims to set standards to reduce man-made underwater acoustic noise that affects marine mammals [14]. Since a variety of methods used for LPD UWAC systems, such as frequency spreading and time reversal, reduce the power spectral density of the transmitted signals, we expect LPD communications to play an important role for a broader class of future UWAC systems.

B. Concept of LPD UWAC

The analysis of fundamental communication-theoretic limits on the achievable throughput of LPD (or covert) communication has received much attention in the recent literature [15], [16]. A "square-root law" for covert communication over the additive white Gaussian noise and more generally discrete memoryless channels has been established in [17], [18], which assumes a shared secret between the legitimate parties of the communication. If the interceptor's channel to the transmitter is noisier than that of the legitimate receiver, then covert communication according to the square-root law can be accomplished also without a pre-shared secret [19], [16], [18]. Extensions have considered scenarios in which the interceptor does not have perfect knowledge about channel statistics and uses a mismatch detector [20] or does not know the transmission time [21]. Furthermore, LPD communication with the aid of a jammer, i.e., an additional, uncoordinated transmitter that helps the communication between a dedicated transmitter-receiver pair remain undetected, has been analyzed [22].

Practical LPD implementations have long been considered for terrestrial radio frequency (RF) and radar applications, e.g. [23], [24], [25]. In [23, Ch. 7], several LPD communication and interception techniques are presented for RF communications. The dominant method is spread-spectrum communication using direct sequence spread spectrum (DSSS) [26]. Extensions that overcome the low channel utilization of conventional DSSS include cyclic code-shift keying modulation schemes [27]. The generated waveforms have a large time-bandwidth product, which leads to a low detection rate comparable to that for DSSS at an interceptor employing an energy detector, but with a better channel utilization. Another spread-spectrum approach for covert communication is based on frequency hopping [28]. Some recent works consider a frequency hopping scheme that changes the carrier frequency in a probabilistic manner aided by spectrum sensing to obtain signal and noise power levels [29]. Cognitive radar techniques [30] that adjust range-angle-dependent beampatterns have been developed to reduce active radar visibility [31]. At the same time, signal processing methods that achieve improved classification of stealth radar signals have been devised as countermeasures [32].

Reliable acoustic communication underwater faces some unique challenges due to the particular signaling method and communication medium, cf. e.g. [33], [34]. Accordingly, also LPD for UWAC requires some UWAC-specific approaches and solutions. First, compared to the propagation models typically used for EM signals, the analysis of LPD for UWAC must consider both the spreading loss and the absorption loss. While absorption loss is also considered in EM channels such as for free-space optical communications or through-wall (indoor-outdoor) RF communication, its effect is prevalent and more significant in underwater acoustics, and the choice of frequency is greatly dependent on this parameter (see for example Figure 3 in [35]). Second, the strong location dependency of the UWAC channel [36], makes it essential to consider different attenuation models for the receiver and interceptor in calculating the LPD capability. Furthermore, without accurate bathymetry information[2] it is difficult to model the UWAC channel reliably and bounds need to be used to calculate the reception and interception ranges. Third, LPD transmission and reception methods are challenged by typically long and fast time-varying channel impulse responses, which require high complexity and fast-convergence equalizers. Moreover, with limited knowledge of the channel, techniques that reuse the channel resources like optimal frequency hopping schemes are not applicable. Directional LPD communication approaches are also difficult to realize due to the small size of underwater platforms relative to the acoustic wave length, and performance can be poor due to non-isotropic noise in the channel. Finally, and beyond LPD, some of the security threats for EM channels as presented in [37] are different than for UWAC. This includes the channel jamming, which would require a huge amount of energy from a jammer in an UWAC scenario, and identity theft and message forging, which are not really applicable for the small number of nodes in UWAC networks.

The objective of this paper is to introduce and review the topic of LPD UWAC for a broad audience and in doing so to stimulate new research and advances in the field. The general scenario we consider for LPD is illustrated in Fig. 2. It consists of a transmitter with an associated legitimate receiver and an interceptor located in some proximity of the transmitter. Given several basic transmission parameters (e.g., the packet duration and the bandwidth of the communication

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[2] Bathymetry refers to a topographic map of the sea bottom with depth indication. Bathymetry is mostly obtained in multibeam surveys.

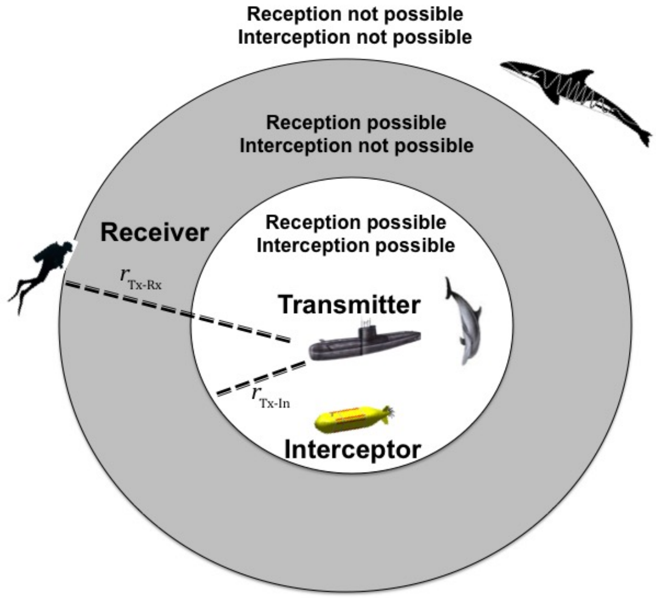

Fig. 2: Typical scenario for LPD UWAC. Interception is possible inside the inner circle. Reception is possible inside the outer circle. The shaded region is suitable for LPD communication.

signal), the interceptor tries to detect the transmitted signal with certain requirements on its false alarm and detection probabilities. Similarly, the receiver is designed to detect and decode the signal with certain targets for its detection and error probabilities.

As illustrated in Fig. 2, the receiver can decode the packet for distances shorter than $r_{\mathrm{Tx-Rx}}$ from the transmitter, while the interceptor cannot detect the packet for distances beyond $r_{\mathrm{Tx-In}}$ from the transmitter. The distances $r_{\mathrm{Tx-Rx}}$ and $r_{\mathrm{Tx-In}}$ are determined according to the target detection probability and symbol error rate at the receiver and the detection and false alarm rates at the interceptor, respectively. The objective of an LPD communication system is to allow reliable communication in a maximal transmission range while minimizing the interception range. Depending on the specific scenario, the interceptor can be assumed to have knowledge of the frequency band of the transmitted signal and possibly even time intervals targeted for communication. However, the interceptor is assumed to be uninformed of the actual waveform parameters of the transmitted signal, and thus cannot perform for example a matched filter operation in order to detect the signal. This is alike the shared secret between transmitter and receiver in information-theoretic studies [16]. Methods for LPD then focus on the ability of the receiver to decode the packet in a very low signal-to-noise power ratio (SNPR).

It is common to consider the minimal SNPR or signal-to-noise ratio (SNR) required by the interceptor (to detect) and the receiver (to decode) as the dominant factors determining the LPD capabilities. For example, in [38] it is claimed that communications should be considered LPD if the nominal SNPR at the receiver is below -8 dB. The authors in [39] set the LPD threshold as a ratio between the SNPR for the transmitter-interceptor link and the SNPR for the transmitter-receiver one, and suggest that LPD should be considered when this ratio is below 6 dB. In this work, we take a more general approach and consider also effects of channel conditions and interceptor capabilities.

While LPD communication has applications in UWAC, only a few works have provided performance analyses. In [40], an analysis is made for the lowest possible transmission power required to obtain a certain channel capacity and LPD capability. The work observes that the minimal required transmission power can be reduced by decreasing the transmission rate and increasing the effective signal bandwidth. Relations are then given between the bandwidth, capacity, and required power allocation per frequency bin. In [41], based on DSSS, an analysis is made for the required source level for a given maximal interception range. In [42], we took a different approach exploring the practical bounds for LPD underwater acoustic communication as a function of the channel characteristics. The presented bounds allow a user to design system parameters for a required LPD capability.

The remainder of this paper is organized as follows. In Section II we identify and discuss the challenges in developing LPD UWAC systems. In Section III, we present common techniques for transmitting and intercepting LPD signals and point out their strengths and weaknesses. In Section IV, we describe quality measures used to determine the LPD capability of UWAC systems, and recommend to use a metric that accounts for the properties of the UWAC channel and abilities of the communication receiver and the interceptor. Sample quantitative performance results including from a sea trial are presented in Section V. Finally, conclusions are drawn in Section VI.

II. CHALLENGES FOR LPD IN UWAC

The main goal in LPD communication is to *hide* the information-bearing signal from an illegitimate receiver, i.e., the interceptor. Similar to the case of EM transmission, in UWAC this is usually done by spreading the signal in frequency [38], [43] or time [44], or by disguising the signal (e.g., as underwater sounds of mammals [45]). However, designing an LPD communication system that makes the transmitted signals undetectable to a possible interceptor while ensuring proper reception is not trivial. In this section, we highlight the design challenges of LPD UWAC systems and discuss ways to approach them. Table I lists the challenges according to where they should be tackled. For completeness, the list also includes challenges experienced at the interceptor.

A. *Channel Related Challenges*

Motion and Synchronization: When the underwater communication nodes are in motion, the signals transmitted experience a Doppler shift. Due to water currents, this Doppler shift is non-negligible even when the nodes are anchored. The motion of the channel itself, due to e.g., waves, currents, etc., induces a Doppler spread that affects equalization. Different than in RF communication, where Doppler effects are mostly compensated for by phase locked loops [23], in UWAC the

TABLE I. Challenges for the design of an LPD system and for the interception of LPD signals.

Transmitter	**Receiver**	**Interceptor**
Attenuation	Channel estimation	Non-Gaussian ambient noise
Spatial dependencies	Non-Gaussian ambient noise	Antenna directivity
Noise directivity	Channel time variation	Complexity
Bandwidth	Synchronization	Time-frequency ambiguity

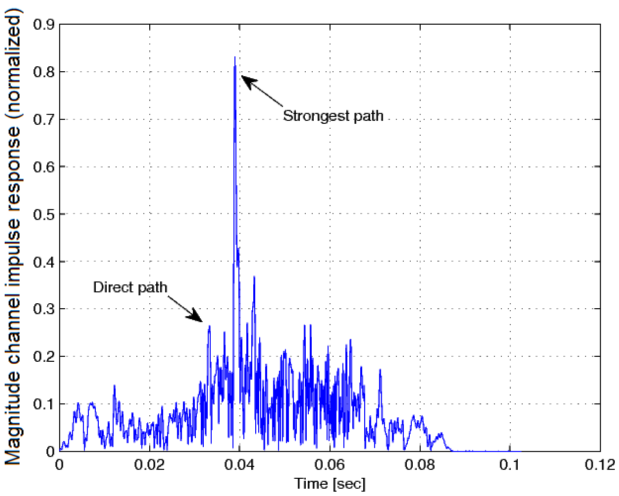

Fig. 3: Normalized magnitude of a channel impulse response measured in a sea trial off the coast of Haifa, Israel, in October 2006. Transmission distance is about 1700 m, water depth is 50 m and carrier frequency is 20 kHz. The delay spread is about 35 ms and the direct path does not correspond to the strongest received echo.

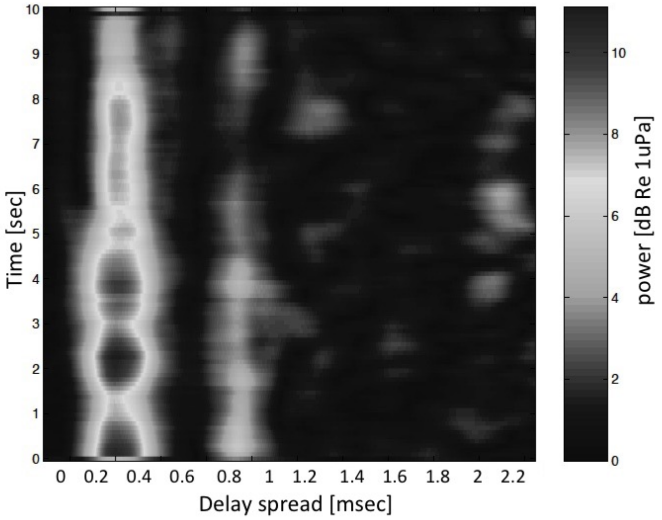

Fig. 4: An example from a sea experiment of a time-varying underwater acoustic channel. The channel was measured in shallow water of 30 m depth with a sandy bottom, and a transmission range of 2500 m. The rows of the image represent the channel impulse responses at different times.

change to the symbol duration is non-negligible and needs to be accounted for. In addition, as demonstrated in Fig. 3, destructive superposition of multipath with the direct path can cause time-synchronization problems. That is, the receiver may falsely regard a multipath arrival as the direct path, and as a result, would not be time synchronized with the transmitter. While an interceptor performing energy detection would not be affected by these challenges, the transmitted packet needs to include synchronization signals. Since these signals increase the packet duration and make it more prone for detection, a common technique is to spread them in time and frequency. At the same time, they need to be resilient to significant Doppler shift and multipath distortions in LPD UWAC, which is accomplished with for example chirp signals [1], [46].

Channel Estimation: Underwater acoustic signals experience channels with long delay spread and fast time variation, which is a significant challenge for UWAC LPD [38]. An example of a time-varying channel impulse response collected from a sea trial is shown in Fig. 4. To estimate the channel, one main approach is to use a training sequence [1]. To increase LPD capability, in [47] a high complexity channel estimation scheme is offered. Decoding at low SNPR was demonstrated in a sea experiment. Since the effect of noise on channel estimation is significant, much like for the synchronization signal, the transmitter may choose to transmit this training sequence at a higher power level than the rest of the communication symbols. Naturally, transmitting extra symbols with possibly high power exposes the transmitter for interception. This is because the interceptor only needs to detect the packet rather than decoding it, and thus it does not require channel estimation. For this reason, for LPD, the preferred approach may be non-coherent communication at the cost of a reduced transmission rate.

Channel Diversity: Due to the complex structure of the underwater channel the transmitter-receiver and transmitter-interceptor links may experience different attenuation-range relations. Since this relation is hard to estimate and since the location of the interceptor is unknown, it is difficult to guarantee an LPD performance. The use of lower and upper

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bounds on channel attenuation is a possible avenue to predict the LPD capability. This is complicated in comparison to typical EM LPD scenarios due to the lack of enough statistical channel analysis for UWAC, and due the need to obtain an extremely accurate bathymetry information for channel modeling, which make it hard to predict the LPD performance.

Hiding Signal in the Ambient Noise: Some LPD systems make use of ambient noise to hide the communication signal, e.g., [48]. This technique requires identification of mutual noise characteristics at the receiver and interceptor locations. The strong signal attenuation in the underwater acoustic channel makes such a characterization challenging. For example, a tonal noise which is significant at the location of the legitimate receiver may be below the noise floor at the interceptor. In addition, since these noise sources are non-isotropic, an interceptor employing a receiving array can differentiate between the transmitted signal and these noise elements. This challenge may be handled by creating spatial focusing at the location of the legitimate receiver.

Noise and Interference: One significant challenge for UWAC is the existence of transient ambient noise components and man-made interference. The former originates from natural sources like snapping shrimps, and the latter is due to underwater equipment such as depth echo-sounders, shipping noise, and sonar systems. Such type of transient noise is unique for UWAC and greatly affects performance [1]. As a result, decoders and detectors tuned to white noise suffer from significant performance degradation. Here, the impact is on both the receiver and the interceptor. The receiver must alleviate impairments from noise and interference via interference cancellation [49], clipping, and noise whitening [50], while the interceptor must adapt its detection thresholds to fit the case of non-isotropic deterministic channel noises. Since decoding requires a much better interference mitigation than detecting, the LPD communication capability is more affected from channel noise than the interceptor.

Bandwidth: Spreading in the frequency domain [26] is an efficient technique in LPD communication. The SNPR at the interceptor decreases with increasing bandwidth. However, different than in many EM transmission scenarios, where the available bandwidth for LPD communication is fairly large compared to the signaling rate, the bandwidth for UWAC is limited by absorption loss and colored noise, and typical values are of the order of only a few kHz [36]. This challenge significantly reduces the LPD capability of UWAC systems.

B. System Related Challenges

Hardware Limitations: Besides limitations due to the hydro-acoustic channel, bandwidth is also limited by the characteristics of the emitter, i.e., the acoustic projector. In particular, at carrier frequencies of tens of kHz, the 3 dB available bandwidth around the resonance frequency of the acoustic projector is usually only a few kHz. This is fundamentally different than for EM communication, where such a hardware limitation does usually not exist [24]. Besides limiting the performance of the LPD UWAC system, the narrow bandwidth makes it easier for the interceptor to lock onto the frequency band of the transmitted signals. Another challenge is the difficulty in employing directional acoustic projectors, and most directional transducers include high side lobes. As a result, directional communication, which improves LPD, is limited and requires the use of large and expensive arrays of transducers for both transmission and reception.

Employing Directivity: To improve LPD, knowledge of the transmitter and/or receiver location, which is not available to the interceptor, can be exploited to apply directivity of signal transmission and/or reception [48]. In RF wireless LPD systems, outdoor locations can be estimated via GPS for example. In UWAC, however, achieving such directivity is challenging. Besides the limitation posed by the design of the transducers, since GPS signals do not propagate underwater it is difficult to obtain reliable location information of a submerged node.

Energy Consumption: LPD communication usually requires transmission with low power. To compensate for the low SNPR, the receiver employs decoding techniques with high computational complexity. This translates directly into increased energy consumption for digital processing. Since for applications of UWAC energy is often a scarce resource and operational longevity is critical, operating an LPD UWAC system is a practical challenge. Energy consumption is also an issue for the interceptor, who may not be aware of the transmission frequency band and needs to employ computational costly simultaneous detection in several suspected bands.

III. APPROACHES FOR LPD UWAC SYSTEMS

In the previous section, we have already mentioned approaches to enable LPD communication underwater. In this section, we present a concise overview of the design options for LPD transmission. We also take the point of view of the adversary and look at methods to improve the success of interception.

A. Transmission Techniques

Table II provides an overview of possible transmission techniques for LPD together with their benefits and disadvantages. In general, LPD signals are designed such that knowledge available at the transmitter or the legitimate receiver but not at the interceptor is exploited. The main types of such signal designs can be classified as signal modulation, transmission scheduling, and spatial focusing.

1) Waveform Design: Bandwidth or time expansion of transmitted signals compared to the underlying data rate provides a processing gain proportional to the expansion. This compression technique enables reception at negative SNPR levels at the legitimate receiver. However, since the interceptor is unaware of the specific transmission structure, it does not benefit from this gain. The most commonly used time-frequency expanded waveforms for underwater LPD acoustic communications are DSSS and chirp signals.

Spread Spectrum - The DSSS signal spreads the communication symbol in frequency, so that the data rate is maintained, but the signal power spectral density is reduced [3]. The DSSS signal is created from a pseudo-random (PN) sequence of

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TABLE II. Transmission techniques for LPD.

Category	Approach	Benefits	Disadvantages
Waveform	DSSS	1) Resilience to ISI 2) Provides "key" for LPD	1) Poor channel utilization 2) High possibility for discovering "key" 3) Requires time-synchronization 4) Sensitive to Doppler shift 5) low transmission rate
	Chirp	1) Low peak-to-average response 2) Resilience to ISI 3) Low channel utilization 4) Resilience to Doppler shift	1) High decoding complexity 2) Easy to track via time-frequency filters
Modulation	**OFDM**	1) Low complexity 2) Resilience to ISI 3) Good channel utilization	1) Sensitive to Doppler shift 2) Challenging peak-to-average response 3) Requires high transmission power per transmission at each frequency band
	Disguising as Mammals	1) High SNPR at receiver 2) Defence against most interceptors	1) Allows short transmissions 2) Difficult to guarantee performance
Scheduling	**Frequency Hopping**	1) Collaborative decoding 2) Provides "key" for LPD	1) Requires time-synchronization 2) Requires bandwidth expansion 3) Sensitive to Doppler shift 4) No resilience to ISI
	Time Hopping	1) LPD with no bandwidth extension 2) Defence against energy detectors	1) Requires time-synchronization 2) Low transmission rate
Focusing	**Directivity**	1) Achieves spatial focusing 2) LPD gain does not depend on channel 3) Reduces environmental impact	1) Requires array of transducers 2) Requires coarse localization capability
	MIMO	1) Reception at low SNPR 2) Noise suppression 3) Reduces environmental impact	1) Requires array of transducers 2) Requires CSI at the transmitter
	Active Time Reversal	1) Small processing effort 2) LPD gain does not depend on channel 3) Reduces environmental impact	1) Requires long channel coherence time 2) Requires active receiver

chips, which in turn is generated from a primitive polynomial. The polynomial is chosen such that the signal's autocorrelation is as narrow as possible. Fig. 5 shows an example of a spread signal that is received below the noise level but is well visible after the de-spreading (or matched filtering).

DSSS-based LPD techniques differ by the design of the spreading sequence. Good LPD attributes of such a sequence are a) a sharp autocorrelation to mitigate ISI, b) a long sequence to spread the signal and reduce its per-Hz power, and c) the use of non-trivial sequences to complicate interception based on a search of the spreading sequence. Spreading can also be done without bandwidth expansion, which allows the use of lower transmit power but at a reduced data rate. In either case, signal detection at the interceptor becomes more difficult, while the receiver, who is aware of the spreading sequence, can still operate at the lower SNPR [38]. As a side effect, when used with lower data rate, DSSS is also a means to make transmission more resilient to inter-symbol interference (ISI) [51]. Several works proposed different spreading techniques to improve the auto-correlation of the DSSS. For example, for improved LPD, [52] proposed non-binary spreading sequences.

However, DSSS is also highly sensitive to Doppler shift and requires accurate time-synchronization [38]. Furthermore, since the spreading sequence serves as the key for LPD spread spectrum communication, it must frequently be changed, which requires collaboration between transmitter and receiver [3].

Chirp - Another widely used signal for UWAC is the chirp signal whose frequency changes with time. Common techniques use linear frequency modulation [53] or hyperbolic or quadratic shape chirps [46]. The wideband characteristics of the chirp signal together with its narrow autocorrelation make it a good modulation signal for LPD communication. Chirp signals enable processing gain similar to those of DSSS signals but without the need to exchange the 'key' PN sequence between the receiver and transmitter [54]. Instead, the receiver should be aware of only the duration and frequency range of the transmitted signal. Due to their time-bandwidth expansion, chirp signals are also considered resilient to Doppler shift

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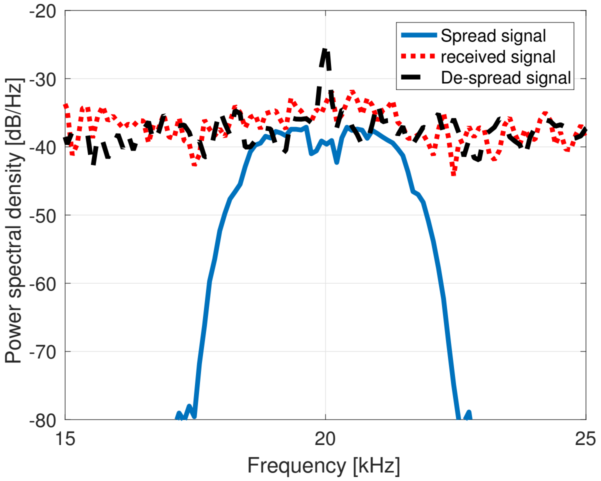


Fig. 5: An illustration of DSSS transmission in the frequency domain. The figure shows the measured PSDs of the received spread signal, the additive noise, and the de-spread signal. Carrier frequency: 20 kHz. Signal duration: 30 ms. SNPR: -5 dB. PN sequence of 127 chips created from a 7 bit polynomial.

[46]. For that reason, chirp signal are often used also as a synchronization signal [55].

An example for the LPD characteristics of a chirp signal is given in Fig. 6. Fig. 6a shows a received noisy chirp signal (red curve) in the frequency domain, where the desired signal (blue curve) is completely hidden below the dominating ambient noise. After the matched filter (Fig. 6b), a well observed peak is received indicating the existence of the signal.

2) Signal Modulation: **OFDM -** Signal spreading in the frequency domain can also be achieved using orthogonal frequency-division multiplexing (OFDM). The long symbol rate at each sub-band enables the transmitter to reduce its source level, and since OFDM uses a simpler equalizer at the receiver, decoding in low SNPRs is possible [43]. Experimental results for multiband OFDM signal are presented in [56] showing communication at rates of up to 78 bits per second with an SNPR of -17 dB. Unlike DSSS where the spreading sequence may change between packets, OFDM does not require strong coordination with the receiver. However, at low SNPR a powerful error correction coding is required and transmission rate decreases. OFDM transmission was also suggested for covert acoustic communications in [39]. The authors presented experimental results showing that when the transmitter was 2000 m from the receiver, an interceptor based on an energy detector was unable to detect the transmitted signals at a distance above 1600 m from the receiver.

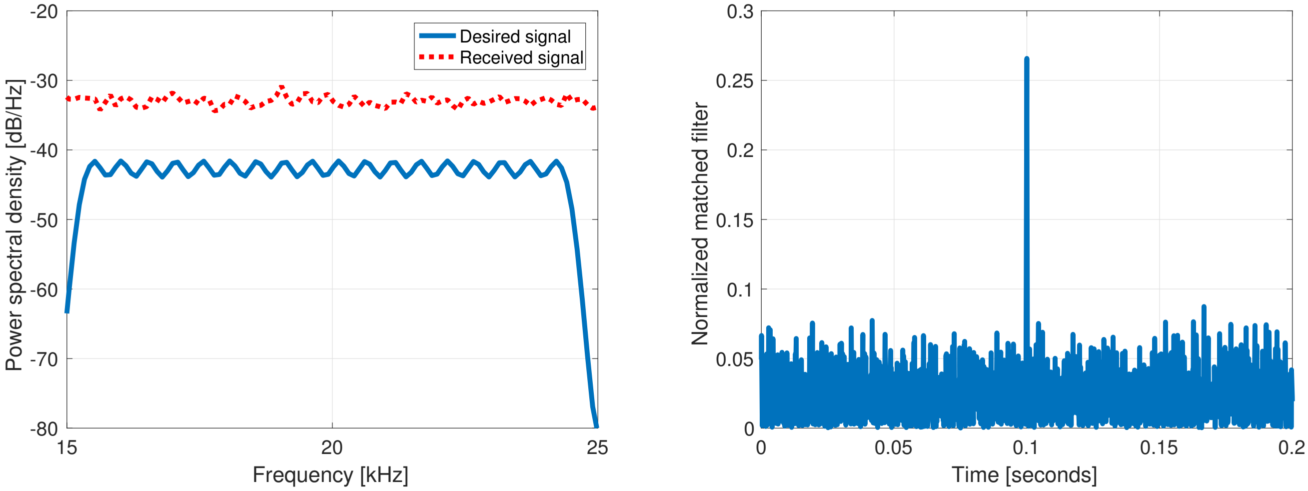
Disguising as Mammals - One technique for LPD that is unique to UWAC is to disguise the transmitted signals as acoustic sounds of marine mammals, usually Dolphins or whales. The signals are chirp-type signals of the same frequencies and durations used by mammals, and are phase modulated. In [45], a Dolphin's click-like modulation signal is used, and a pulse position modulation scheme is applied to disguise the communication as high frequency click emissions. The same authors extended this approach in [57] to base LPD underwater acoustic communication on Dolphin's whistles. A minimum shift keying modulation signal is marked over the contour of the whistle-like signal. Assuming the interceptor cannot determine the signal as a communication signal, the emissions are performed with a high power allowing LPD communication at a high transmission rate. In [58] mimicking biological sounds is used to disguise DSSS signals. The transmitted DSSS signals are hidden below relatively high-power whale-like signal transmissions. Knowing the shape of the disguising signal, the receiver uses interference cancellation to suppress the strong whale-like signals. Sounds of Humpback whales are also utilized as a camouflage for sonar activity in [59].

Disguising the transmitted signal as sound emissions from marine mammals provides a defence against most interceptors, and interception is possible only if combined with other means, e.g., imaging techniques to validate mammal detection. Moreover, since the signals are transmitted with relatively high power, reception capability is high. However, to make the transmission seem natural, the transmission rate is quite limited. More importantly, while, given a reference interception method, the performance of other techniques for LPD UWAC can be evaluated, here the transmitter can never be sure if the disguise works and thus LPD performance cannot be guaranteed.

3) Transmission Scheduling: **Frequency Hopping -** In this method, the carrier frequency of the transmitted signal changes with time at the symbol or even sub-symbol rate. The receiver, who is aware of the hopping pattern, is able to reconstruct the signal while being exposed to noise in the currently used (narrow) frequency band [60]. On the other hand, much like in DSSS, to collect all energy the interceptor needs to open a wide bandwidth window. Frequency hopping requires coordination with the receiver, and a bandwidth expansion. To resolve this, [61] offered to combine frequency hopping in the form of frequency shift keying modulation with phase shift keying modulation. To reduce the detection probability of the signals by an interceptor, the transmitted signals are made extremely short and the receiver synchronize on the signal in the frequency-phase domain. In case of coherent detection, since frequency changes fast it is difficult to track the channel. In addition, due to the limited bandwidth available for UWAC, this method is sensitive to Doppler shift.

Time Hopping - Assuming the interceptor does not have infinite memory resources, it either relies on a-priori information regarding the packet duration or it processes received signal samples starting from a rise in detected energy and until the energy level drops. As a countermeasure to such interception, the transmitter can introduce pseudo-random time gaps between the symbols of a data packet. Such an approach appears in [45], where the modulation follows a time hopping pattern known to both the transmitter and receiver.

4) Spatial Focusing and Decoding: **Directivity -** Prior knowledge of the locations of the transmitter and receiver can be used for spatial signal focusing via directional reception and transmission, respectively. As a result, the transmission



(a) Transmitted and received Chirp signal.

(b) Output of normalized matched filter for chirp.

Fig. 6: Figure shows that a received chirp signal below the noise level is still well detected by a matched filter. Signal arrives 0.1 seconds after beginning of reception. Carrier frequency: 20 kHz. Signal duration: 0.1 s. SNPR: -10 dB.

power can be reduced and directional noise components are mitigated. While maintaining accurate location information is difficult once the underwater nodes are submerged, a coarse direction information is already quite useful for transmitter and receiver spatial focusing [62]. However, signal directivity requires an array of transducers, which may be not be available for some cases (e.g., diver) and become too large for others (e.g., AUV).

MIMO - If channel state information (CSI) is available at the transmitter, spatial focusing can be achieved through beam-forming, signal alignment, or multi-input-multi-output (MIMO) transmission. In case beam forming is produced at the transmitter, directivity is obtained and the received power at the interceptor reduces. Still, size constraints of the transmitter and receiver vessels limit the use of such systems.

Time Reversal - In LPD UWAC, the PSD of the transmitted signals is low. To increase the SNPR at the legitimate receiver, one option is to employ spatial focusing through active time-reversal modulation. In his method, the phase conjugate of a probe signal sent by the receiver is used by the transmitter as the modulation signal [44]. Assuming a reciprocal channel and since the channel impulse response is location-dependent, the time-reversed signal becomes focused at the receiver location but spread at the interceptor. However, active time-reversal requires a channel coherence time longer than the propagation delay of the probe and data signals. As an alternative, a passive time-reversal technique is used in [57] to focus the energy of DSSS signals.

Decoding - Another approach to improve LPD capability are decoding techniques designed specifically for low SNPR. At the cost of computational complexity, these techniques try to accumulate the power received from all multipath arrivals. In [63], Turbo equalization is performed for DSSS signals at the aim of decoding in a very low SNPR. The method combines the advantages of convolutional channel coding with the bandwidth extension of DSSS to allow reception at a low SNPR. Simulations and a lake experiment validated reception for SNPRs below -10 dB for a large bandwidth extension using a 16 bit pseudo random sequence. Differently, [64] uses strong emissions of whale-like noises to disguise the communication signal and to allow accurate channel estimation, which is the same for the disguising noise and the communication signal.

B. *Interception Techniques*

While the interceptor may have other tasks such as jamming the communication signal or locating the source [24, Ch. 5], we focus on its primary goal, namely, to detect the transmitted signal even at a large distance from the transmitter. It is assumed that the interceptor has knowledge of basic signal features such as the bandwidth and duration of the transmitted signals. Without the knowledge of the signal structure, the available literature on detecting LPD UWAC signals follows the approaches for interception of LPD signals over EM channels that are surveyed in [23, Ch. 6]. In this section, we introduce common methods for interception of UWAC signals. In Table III we list the pros and cons of several interception techniques.

With no information about the signal format and modulation, the most common interceptor type is the energy detector, often called radiometer. Considering the colored ambient noise, the received signal is filtered by a whitening filter and then its energy within an interval of the signal duration is measured. The result of the energy detector is compared with a threshold to decide whether a signal is present or not. A common detection approach in energy detectors is to use a constant false alarm rate (CFAR). The threshold is calculated as a function of the desired false alarm probability and the statistics of the measured noise [36]. While interception based on energy detection does not depend on the transmitted signal,

TABLE III. Interception techniques.

Approach	Benefits	Disadvantages
Energy Detection	1) No need for pre-knowledge of signal structure 2) CFAR system	1) Poor performance against spread spectrum 2) Performance greatly degrades for complex channels
Pattern Recognition	1) Utilizes knowledge regarding signal 2) Effective against spread spectrum techniques	1) Requires prior information of signal parameters 2) Cannot handle a fast fading channel
Cyclostationary Detection	1) No prior knowledge of signal needed 2) Good performance against spread spectrum 3) Robustness to channel changes	1) Sensitive to correlated noise 2) Poor performance at low SNPR

its performance depends on the channel conditions. Fast time-varying noise level and outliers like tonal noises and transients, and the need to collect noise from a large frequency band while performing noise whitening based on noise estimation or possibly mismatched models affect the false alarm rate of the interceptor.

Since it is known that LPD UWAC usually uses either DSSS signaling or frequency- or time-hopping communications, alternative detectors that match these types of transmission can be considered.

Multiple-band energy detector - This detector performs detection at multiple bands, each of which is exposed to less noise than the conventional full-band energy detector [36]. As a result, the detector can combat frequency hopping techniques and prior information of the frequency band of the transmitted signal is not required.

Pattern recognition detector - This detector searches for specific waveforms at a target frequency band. Common examples are detectors for DSSS signals that search for several candidate DSSS chip rates [65], and detectors for chirp signals that tries to match received signals with chirp of different time-frequency slop [66]. It is sensitive to transients and to fluctuations in the noise level though [67].

Cyclostationary-feature detector - This detector uses spectral analysis to reveal cyclostationary features of LPD communication signals. For example, a simple technique is to detect fluctuations of second order [68]. This detector may fail when the ambient noise consists of correlated components (e.g., background tonal shipping noise) or when the noise power fluctuates. Feature extraction is also offered in [69], where the communication modulation type is determined from analyzing time-frequency images.

IV. MEASURES FOR LPD

An important factor in designing LPD systems is a proper measure for the LPD capability. In this section, we consider current alternatives to measure how covert a communication system is, and we recommend an amended range-ratio test LPD measure.

A. Measures Used in Literature

One of the most common LPD performance measures for terrestrial RF and for radar applications is the so called *detectability distance* [70]. This measure defines the LPD based on the range for which the interceptor's detection probability is above a required value. This way, two LPD systems are compared by fixing the false alarm rate. Other approaches compare the ratio between the SNR at the output of the matched filter for the legitimate receiver and the SNPR at the input to interceptor, or the minimum SNPR for which the receiver can still decode the packet [3]. However, neither of these measures combines together the specific capabilities of the receiver and interceptor.

LPD capability is also directly measured by means of the detection probability of the interceptor [45], or, for frequency hopping communication, as a function of the rate of frequency hops [60]. In [40], LPD is achieved if the SNPR at each frequency band is below a threshold, as experienced by the interceptor. Another approach is to consider LPD as the difference between the reception and detection gains of the receiver and interceptor, respectively [71]. These gains include the path loss, channel coding, and antenna gains.

B. Recommended LPD Measure

Based on the above discussion, in this section we recommend to measure the LPD performance based on a measure that captures both the capabilities of the receiver and the interceptor while considering the parameters of the channel for both the transmitter-receiver link and the transmitter-interceptor link. Specifically, we consider the simplified model for the power transmission loss at range r [72],

$$T_{\mathrm{L}}(r) = \gamma \log_{10}\left(\frac{r}{1\ \mathrm{m}}\right) + A(\gamma) + \alpha(\omega)\frac{r}{1000\ \mathrm{m}}\ , \tag{1}$$

where γ is the spreading parameter, $\alpha(\omega)$ is the attenuation parameter at frequency ω, and the function A depends on the structure of the channel.

Let us now define the spreading parameters $\gamma_{\mathrm{Rx}}, \gamma_{\mathrm{In}}$ and the absorption parameters $\alpha_{\mathrm{Rx}}, \alpha_{\mathrm{In}}$, for signals received at the receiver and interceptor, respectively. Also consider a receiver with target symbol error rate P_{e}, and an interceptor with detection and false alarm rates P_{d} and P_{fa}, respectively. Then, adapting the concept of *range ratio* test from [70], we recommend to measure the LPD capability as

$$\rho_{\mathrm{LPD}} = \frac{r_{\mathrm{Tx-In}}\left(P_{\mathrm{d}}, P_{\mathrm{fa}}, \gamma_{\mathrm{In}}, \alpha_{\mathrm{In}}\right)}{r_{\mathrm{Tx-Rx}}\left(P_{\mathrm{e}}, \gamma_{\mathrm{Rx}}, \alpha_{\mathrm{Rx}}\right)}\ , \tag{2}$$

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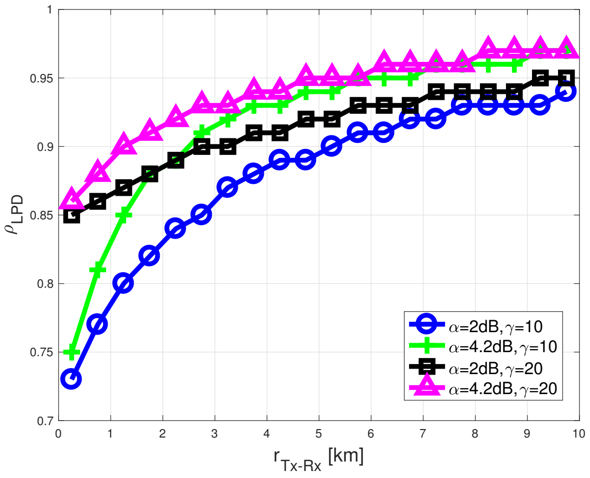

Fig. 7: Measure ρ_{LPD} as a function of $r_{\mathrm{Tx-Rx}}$. Numerical results from (2) using the bounds from [42]. LPD UWAC is possible above curves.

which includes channel transmission loss parameters. The calculations of $r_{\mathrm{Tx-In}}$ and $r_{\mathrm{Tx-Rx}}$ are performed by identifying the minimum required SNPRs to reach the target P_{e}, P_{d} and P_{fa}, and by employing model (1). Measure (2) should be treated like a bound for LPD communications. Specifically, by setting bounds over the spreading parameters γ_{Rx} and γ_{In} and over the absorption parameters α_{Rx} and α_{In} as in [72], one can obtain lower and upper bounds for the LPD capability as shown in [42]. Tighter bounds can be found in case the channel impulse response is known. Here, a fading channel model would replace the simple model (1), if not analytically then based on Monte-Carlo simulations using numerical models, e.g., [73].

Note that the LPD performance increases as ρ_{LPD} decreases. As illustrated in Fig. 2, $r_{\mathrm{Tx-In}}$ is the interception range, defined as the maximum range in which the interceptor can detect the signals according to a target detection and false alarm rates. Similarly, $r_{\mathrm{Tx-Rx}}$ is defined as the maximum transmission distance at which the legitimate receiver can decode the packet with a desired packet error probability. The recommended measure ρ_{LPD} does not depend on the absolute transmission power and allows a representation of LPD for each desired reception range. Measure ρ_{LPD} also gives the user the flexibility to choose its LPD performance as a function of the desired transmitter-receiver distance. Furthermore, as in [70], the range test ρ_{LPD} does not depend on the type of communications. That is, it can fit both narrowband and wideband interferences.

V. PERFORMANCE RESULTS

This work focuses on surveying current approaches for LPD communication in underwater acoustics, and aims to encourage further research in this field. While we do not present a comprehensive performance evaluation of LPD performance, in this section we show some informative results from numerical analysis and from a sea experiment that are based on the recommended LPD measure ρ_{LPD}.

A. Numerical Analysis

Our analysis is based on finding the expression for the minimal SNPR required for message decoding at a target symbol error rate P_{e}, and the minimal SNPR at which the interceptor can detect the transmitted signals at a target false alarm P_{fa} and detection probability P_{d}. Then, applying the propagation model (1), we calculate the maximal transmitter-receiver range as well as the maximal transmitter-interceptor range and compute our LPD measure (2) as a function of the channel's absorption loss, α, and the spreading loss parameter, γ.

We consider the simple case of an interceptor applying an energy detector, and assume the interceptor has full knowledge of the signal bandwidth W and the signal duration T. In these conditions, the receiver operating characteristic (ROC) of the interceptor is expressed by

$$\mu_{\mathrm{In}} = \sqrt{\frac{2}{WT}}\left(\operatorname{erfc}^{-1}(2P_{\mathrm{fa}}) - \operatorname{erfc}^{-1}(2P_{\mathrm{d}})\right) \cdot \frac{1}{G_{\mathrm{In}}} \ . \tag{3}$$

where μ_{In} and G_{In} are the interceptor SNPR and transducer gain, respectively.

For the transmitting signal, we assume that a packet comprises of 100 DSSS symbols with $L = 128$ chips and a duration of 10 ms. As in the JANUS standard for underwater acoustic communication [74], the symbols are assumed M-ary orthogonal modulated, for which [75, Eq. (5.2-61)]

$$P_{\mathrm{e}} = \sum_{m=1}^{M-1} (-1)^{m+1} \binom{M-1}{m} \frac{1}{m+1} \exp\left(\frac{-mLG_{\mathrm{Rx}}\mu_{\mathrm{Rx}}}{m+1}\right) , \tag{4}$$

where μ_{Rx} and G_{Rx} are the receiver SNR and transducer gain, respectively.

Assuming $P_{\mathrm{e}} = 10^{-4}$, $P_{\mathrm{fa}} = 10^{-4}$, $P_{\mathrm{d}} = 0.5$, $M = 16$, $W = 2500$ Hz, and for simplicity $G_{\mathrm{Rx}} = G_{\mathrm{In}} = 1$, Fig. 7 shows the measure ρ_{LPD} as a function of $r_{\mathrm{Tx-Rx}}$ for several values of channel parameters with $\alpha_{\mathrm{In}} = \alpha_{\mathrm{Rx}} = \alpha$ and $\gamma_{\mathrm{In}} = \gamma_{\mathrm{Rx}} = \gamma$. LPD communication is possible for distance ratios above the curves. For example, for $\alpha = 2$ dB/km and $\gamma = 10$, and $r_{\mathrm{Tx-Rx}} = 2$ km, an interceptor located more than 1.7 km away from the transmitter would not be able to detect the communication. Fig. 7 shows that LPD capability improves as power attenuation in the channel decreases.

Since the communication bearing symbols are usually preceded by a synchronization signal, it is also of interest to measure the LPD capability in terms of the receiver capability to decode the synchronization signal vs. the interceptor's capability to detect it. Since time synchronization is of great importance for the overall decoding process, the synchronization signal is usually longer than the communication signals. While the interceptor's operation is similar in the cases of detecting the synchronization signal and detecting the communication signal, the receiver's task is easier. Here, knowing the structure of the signal, the receiver can correlate the received signal with a template of the synchronization signal, and compare the result to a pre-defined threshold set by, for example, the target false alarm rate. In this case, the relation between the

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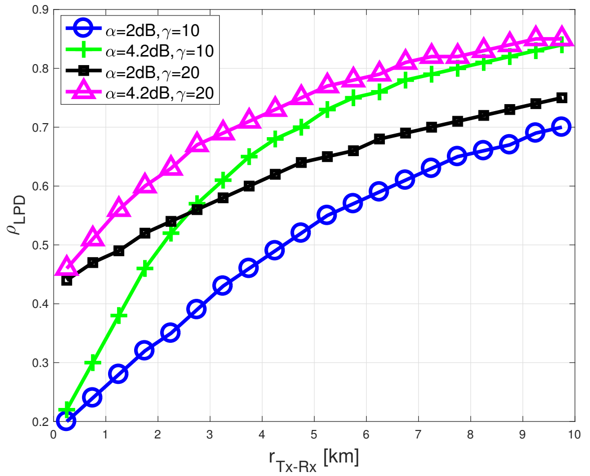

Fig. 8: Measure $\rho_{\rm LPD}$ as a function of $r_{\rm Tx-Rx}$ for the detection and interception of a synchronization signal. LPD UWAC is possible above curves.

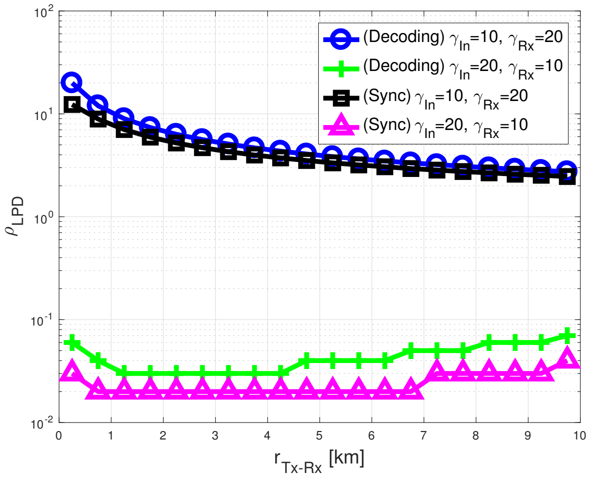

Fig. 9: Measure $\rho_{\rm LPD}$ as a function of $r_{\rm Tx-Rx}$ for the decoding receiver and synchronizing receiver with different spreading parameter for the receiver and interceptor. $\alpha = 2$ dB for both interceptor and receiver. LPD UWAC is possible above curves.

detection probability, is (see details in [42])

$$\mu_{\rm Rx} = \frac{1}{W T_{\rm sync} G_{\rm Rx}} \left(\text{erfc}^{-1}(2P_{\rm fa}^{\rm Rx}) - \text{erfc}^{-1}(2P_{\rm d}^{\rm Rx})\right)^2 , \qquad (5)$$

where $P_{\rm fa}^{\rm Rx}$ and $P_{\rm d}^{\rm Rx}$ are the false alarm and detection probabilities for synchronization and $T_{\rm sync}$ is the synchronization signal duration. Fig. 8 shows the LPD performance for the synchronization signal as a function of the channel parameters, where we used $W = 2000$ Hz, $T_{\rm sync} = 0.1$ s, $P_{\rm fa}^{\rm Rx} = 10^{-3}$, $P_{\rm d}^{\rm Rx} = 0.9$, and for the interceptor, $P_{\rm fa} = 10^{-4}$ and $P_{\rm d} = 0.5$. Comparing the results with those of Fig. 7, we observe that the LPD performance for time synchronization is better than for decoding. For example, for $\alpha = 2$ dB, $\gamma = 10$ dB, and a transmission distance of 1 km, the LPD measure is 0.83 for decoding compared to 0.35 for time synchronization. This result suggests that for the chosen parameter settings, the synchronization signal is less detectable than the information-bearing signal.

Another interesting result is the LPD performance when the channel spreading parameter is different for the receiver and the interceptor. This case occurs when the interceptor and receiver are located in different environments, e.g., in shallow and in deeper water, or when the receiver is unable to collect all the energy of the received signal, e.g., it locks onto only one arrival path. Results for both a decoding receiver and a synchronizing receiver are shown in Fig. 9. We observe that there is a huge difference in LPD performance for different pairs of spreading parameters. For example, for a transmission distance of 2 km, when the receiver is in shallow water ($\gamma_{\rm Rx} = 10$) while the interceptor is in deeper water ($\gamma_{\rm In} = 20$), the LPD measure is 0.03 for decoding and 0.02 for synchronization. In the reverse scenario, the LPD measure greatly deteriorates to 7 for decoding and 6 for synchronization. We therefore conclude that LPD performance in areas of complex bathymetry is much harder to predict.

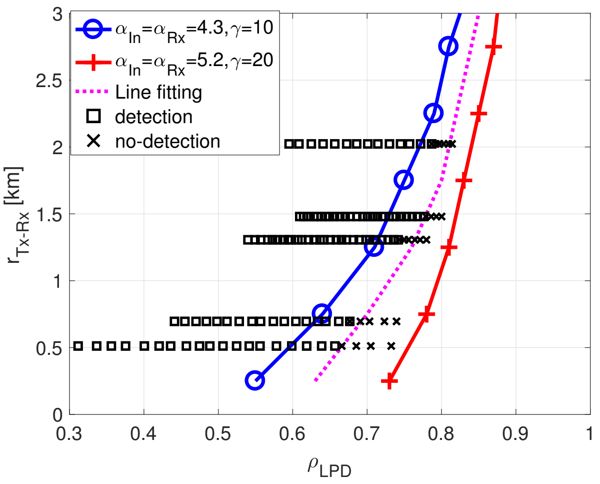

Fig. 10: Results from a sea trial as a function of channel parameters (1). Transmitted signal was a DSSS of 128 chips with a carrier frequency of 30 kHz. Results show an agreement between the LPD bounds and the actual interception results.

B. Experimental Results

In [42], we have described the results from a sea experiment, where we have tested underwater acoustic LPD communications. The experiment took place in June 2013 in the Saanich Inlet, Vancouver Island, Canada, and included a static transmitter (ITC 1032) located on the Venus node in the inlet at a water depth of 75 m (see [76]), and two receivers (ITC 1042) placed on mobile vessels. The transmitter was connected to a power amplifier and periodically communicated packets of 100 DSSS symbols at a source level of 170 dB Re 1μPa/V @1m, with the same characteristics as in the above analysis, and in the frequency range of 25-35 kHz. Each receiver included a single hydrophone with similar sensitivity of -200 dB Re 1V/μPa. The decoding and interception of signals was performed on a laptop connected to the hydrophones through a data-acquisition board.

The experiment included transmission at five different source levels. For each source level, the receiver was placed at the maximal distance for which the symbol error rate of 1% was achieved. This yielded the five transmitter-receiver distances 0.5 km, 0.75 km, 1.4 km, 1.5 km, and 2 km. For each distance, starting close to the transmitter, the interceptor moved in intervals of about 20 m toward the receiver while trying to detect the transmitted signals. The process stopped when interception failed.

The experimental results are shown in Fig. 10 in terms of the recommended range test (2), and are marked by squares in case the interceptor was able to detect the signal and by crosses otherwise. For example, when the transmitter-receiver distance was 500 m, LPD communication was possible for $\rho_{\text{LPD}} = 0.65$. Fig. 10 also shows theoretical upper and lower LPD bounds calculated from (2) for two different assumed channel spreading and absorption parameters. The interception performance achieved agree with those bounds.

VI. CONCLUSION

Low probability of detection (LPD) for underwater acoustic communication (UWAC) is an important topic not only for military applications, but also for civilian use due to the environmental effects of sound transmission in the ocean. The latest advance in hydro-acoustic technology and the growing use of autonomous underwater vehicles has led to an increase in interception capabilities. As a result, considerable effort has been invested into improving the ability of the receiver to decode packets in low signal-to-noise power ratios and on developing new techniques for hiding the transmitted signal in the ambient noise. In this paper, we identified the challenges in the design of LPD UWAC in terms of both channel effects and system capabilities. We classified the common approaches for transmitting, receiving, and intercepting of hydro-acoustic LPD signals, and discussed methods to determine the LPD capability. We recommended to use a range test as a measure for LPD communication which considers the capabilities of the receiver and interceptor and accounts for the UWAC channel characteristics. Based on this measure, we showed the capabilities of traditional LPD communication and interception techniques using numerical simulations and measurements in a sea experiment. The results revealed the large effect of the channel transmission loss parameters on the LPD capability.

REFERENCES

[1] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," *Journal of Marine Technology Society*, vol. 42, no. 1, pp. 103–116, 2008.

[2] J. D. Park, D. J. Miller, J. F. Doherty, and S. C. Thompson, "Feasibility of range estimation using sonar LPI," in *Conference on Information Sciences and Systems (CISS)*, Mar. 2010, pp. 1–6.

[3] J. Ling, H. He, J. Li, W. Roberts, and P. Stoica, "Covert underwater acoustic communications," *The Journal of the Acoustical Society of America*, vol. 128, no. 5, pp. 2898–2909, 2010.

[4] C. Lal, R. Petroccia, M. Conti, and J. Alves, "Secure underwater acoustic networks: Current and future research directions," in *IEEE Underwater Communications and Networking Conference (UComms)*, Aug. 2016, pp. 1–5.

[5] P. Tyack, "Human-generated sound and marine mammals," vol. 62, no. 11, pp. 39–44, 2009.

[6] S. Sendra, J. Lloret, J. M. Jimenez, and L. Parra, "Underwater acoustic modems," *IEEE Sensors Journal*, vol. 16, no. 11, pp. 4063–4071, Jun. 2016.

[7] M. McKenna, D. Ross, S. Wiggins, and J. Hildebrand, "Underwater radiated noise from modern commercial ships," *Acoustic Society of America*, vol. 131, no. 1, pp. 92–103, Jan. 2012.

[8] V. V. Popov, A. Y. Supin, V. V. Rozhnov, D. I. Nechaev, and E. V. Sysueva, "The limits of applicability of the sound exposure level (SEL) metric to temporal threshold shifts (TTS) in Beluga whales, Delphinapterus Leucas," *The Journal of Experimental Biology*, vol. 217, no. 10, pp. 1804–1810, 2014.

[9] W. W. Clark, "Recent studies of temporary threshold shift (TTS) and permanent threshold shift (PTS) in animals," *The Journal of the Acoustical Society of America*, vol. 90, no. 1, pp. 155–163, 1991.

[10] "Ultrasound, environmental health criteria," *WHO/IRPA Task Group on Environmental Health Criteria for Ultrasound*, no. 22, Jan. 1982.

[11] C. Howard, C. Hansen, and A. Zender, "Review of current recommendations for airborne ultrasound exposure limits," in *Acoustics*, Bussoleton, Australia, Nov. 2005.

[12] "Noise from commercial shipping and its adverse impacts on marine life," *Marine Environment Protection Committee, Agenda item 17*, no. 66, Nov. 2011.

[13] N. A. de Soto, K. Gkikopoulou, S. Hooker, S. Isojunno, M. Johnson, P. Miller, P. Tyack, P. Wensveen, C. Donovan, C. Harris *et al.*, "From physiology to policy: A review of physiological noise effects on marine fauna with implications for mitigation," in *Meetings on Acoustics*, vol. 27, no. 1, 2016, p. 040008.

[14] M. Ritts, "Amplifying environmental politics: Ocean noise," *Antipode*, 2017.

[15] A. O. Hero, "Secure space-time communication," *IEEE Transactions on Information Theory*, vol. 49, no. 12, pp. 3235–3249, Dec. 2003.

[16] B. Bash, D. Goeckel, D. Towsley, and S. Guha, "Hiding information in noise: fundamental limits of covert wireless communication," *IEEE Communications Magazine*, vol. 53, no. 12, pp. 26–31, Dec. 2015.

[17] B. A. Bash, D. Goeckel, and D. Towsley, "Covert communication gains from adversarys ignorance of transmission time," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8394–8405, Dec 2016.

[18] M. Bloch, "Covert communication over noisy channels: A resolvability perspective," *IEEE Transactions on Information Theory*, vol. 62, no. 5, pp. 2334–2354, May 2016.

[19] P. Che, M. Bakshi, and S. Jaggi, "Reliable deniable communication: Hiding messages in noise," in *2013 IEEE International Symposium on Information Theory*, Jul. 2013, pp. 2945–2949.

[20] S. Lee, R. J. Baxley, M. A. Weitnauer, and B. Walkenhorst, "Achieving undetectable communication," *IEEE Journal of Selected Topics in Signal Processing*, vol. 9, no. 7, pp. 1195–1205, Oct. 2015.

[21] B. Bash, D. Goeckel, and D. Towsley, "LPD communication when the warden does not know when," in *IEEE International Symposium on Information Theory*, Jun. 2014, pp. 606–610.

[22] T. Sobers, B. A. Bash, S. Guha, D. Towsley, and D. Goeckel, "Covert communication in the presence of an uninformed jammer," *IEEE Transactions on Wireless Communications*, vol. 16, no. 9, pp. 6193–6206, Sep. 2017.

[23] D. Adamy, *EW 101: A first course in electronic warfare*. Artech house, 2001, vol. 101.

[24] ——, *EW 102: A second course in electronic warfare*. Artech House, 2004.

[25] ——, *EW 103: Tactical battlefield communications electronic warfare*. Artech House, 2008.

[26] M. K. Simon, J. K. Omura, R. A. Scholtz, and B. K. Levitt, *Spread spectrum communications handbook*. McGraw-Hill, New York, 1994.

[27] G. M. Dillard, M. Reuter, J. Zeiddler, and B. Zeidler, "Cyclic code shift keying: A low probability of intercept communication technique," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 39, no. 3, pp. 786–798, 2003.

[28] N. Beaulieu, W. Hopkins, and P. McLane, "Interception of frequency-hopped spread-spectrum signals," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 5, pp. 853–870, Jun. 1990.

[29] B. Ning, Z. Li, L. Guan, and F. Zhou, "Probabilistic frequency-hopping sequence with low probability of detection based on spectrum sensing," *IET Communications*, vol. 11, no. 14, pp. 2147–2153, 2017.

[30] S. Haykin, "Cognitive radar: A way of the future," *IEEE Signal Processing Magazine*, vol. 23, no. 1, pp. 30–40, Jan. 2006.

[31] J. Xiong, W. Q. Wang, C. Cui, and K. Gao, "Cognitive FDA-MIMO radar for LPI transmit beamforming," *IET Radar, Sonar Navigation*, vol. 11, no. 10, pp. 1574–1580, 2017.

[32] T. R. Kishore and K. D. Rao, "Automatic intrapulse modulation classification of advanced LPI radar waveforms," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 53, no. 2, pp. 901–914, Apr. 2017.

[33] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 84–89, January 2009.

[34] P. A. van Walree, "Propagation and scattering effects in underwater acoustic communication channels," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 4, pp. 614–631, Oct 2013.

[35] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 11, no. 4, pp. 34–43, 2007.

[36] W. Burdic, *Underwater Acoustic System Analysis*. Los Altos, CA, USA: Peninsula Publishing, 2002.

[37] Y. Zou, J. Zhu, X. Wang, and L. Hanzo, "A survey on wireless security: Technical challenges, recent advances, and future trends," *Proceedings of the IEEE*, vol. 104, no. 9, pp. 1727–1765, 2016.

[38] T. Yang and W. Yang, "Performance analysis of direct-sequence spread-spectrum underwater acoustic communications with low signal-to-noise-ratio input signals," *Journal of Acoustical Society of America*, vol. 123, no. 2, pp. 842–855, Feb. 2008.

[39] P. Walree, T. Ludwig, C. Solberg, E. Sangfelt, A. Laine, G. Bertolotto, and A. Ishy, "UUV covert acoustic communications," in *Underwater Defence Technologies (UDT)*, Hamburg, Germany, 2006.

[40] T. G. Dvorkind, "Power allocation for covert communication, with application to underwater acoustic channel," in *IEEE International Conference on the Science of Electrical Engineering (ICSEE)*, Nov. 2016, pp. 1–5.

[41] T. C. Yang and W. B. Yang, "Low probability of detection underwater acoustic communications for mobile platforms," in *MTS/IEEE OCEANS*, Sep. 2008, pp. 1–6.

[42] R. Diamant, L. Lampe, and E. Gamroth, "Bounds for low probability of detection for underwater acoustic communication," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 1, pp. 143–155, Jan. 2017.

[43] G. Leus, P. Walree, J. Boschma, C. Franciullacci, H. Gerritsen, and P. Tusoni, "Covert underwater communication with multiband OFDM," in *MTS/IEEE OCEANS*, Quebec City, Canada, Sep. 2008.

[44] H. Song, P. Roux, W. Hodgkiss, W. Kuperman, T. Akal, and M. Stevenson, "Multiple-input-multiple-output coherent time reversal communications in a shallow-water acoustic channel," *IEEE J. Oceanic Eng.*, vol. 31, no. 1, pp. 170–178, Jan. 2006.

[45] S. Liu, G. Qiao, and A. Ismail, "Covert underwater acoustic communication using dolphin sounds," *The Journal of the Acoustical Society of America*, vol. 133, no. 4, pp. EL300–EL306, 2013.

[46] R. Diamant, A. Feuer, and L. Lampe, "Choosing the right signal: Dopplerx shift estimation for underwater acoustic signals," in *ACM International Conference on Underwater Networks and Systems*, 2012, p. 27.

[47] P. Walree, E. Sangfelt, and G. Leus, "Multicarrier spread spectrum for covert acoustic communications," in *MTS/IEEE OCEANS*, Quebec City, Canada, Sep. 2008.

[48] Y. Heda and R. Shah, "Covert channel design and detection techniques: A survey," in *IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, Jul. 2015, pp. 1–6.

[49] S. Cho, H. Song, and W. Hodgkiss, "Successive interference cancellation for underwater acoustic communications," *IEEE Journal of Oceanic Engineering*, vol. 36, no. 4, pp. 490–501, 2011.

[50] X. Kuai, H. Sun, S. Zhou, and E. Cheng, "Impulsive noise mitigation in underwater acoustic OFDM systems," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 8190–8202, Oct. 2016.

[51] L. Lei and F. Xu, "A chaotic direct sequence spread spectrum communication system in shallow water," in *International Conference on Control, Automation and Systems Engineering (CASE)*, Singapore, Jul. 2011.

[52] H. W. Lee, E. H. Jeon, T. I. Kwon, K. M. Kim, D. W. Lee, and T. D. Park, "Design of orthogonal code for covert underwater acoustic communication," in *MTS/IEEE OCEANS*, Apr. 2016, pp. 1–4.

[53] M. Palmese, G. Bertolotto, A. Pescetto, and A. Trucco, "Experimental validation of a chirp-based underwater acoustic communication method," in *Meetings on Acoustics*, vol. 4, no. 1, 2008.

[54] B. G. Mobasseri and A. Lulu, "LPI waveform design using chirplet graphs," in *MTS/IEEE OCEANS*, Oct. 2015, pp. 1–6.

[55] R. Diamant, "Closed form analysis of the normalized matched filter with a test case for detection of underwater acoustic signals," *IEEE Access*, vol. 4, pp. 8225–8235, 2016.

[56] G. Leus and P. A. van Walree, "Multiband OFDM for covert acoustic communications," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 9, pp. 1662–1673, Dec. 2008.

[57] S. Liu, T. Ma, G. Qiao, and B. Kuang, "Bionic communication by dolphin whistle with continuous-phase based on MSK modulation," in *IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*, Aug. 2016, pp. 1–5.

[58] S. Liu, G. Qiao, A. Ismail, B. Liu, and L. Zhang, "Covert underwater acoustic communication using whale noise masking on DSSS signal," in *MTS/IEEE OCEANS*, Jun. 2013, pp. 1–6.

[59] Q. Wang, L. Wang, and L. Zou, "Whale-inspired sonar in covert detection," in *IEEE/OES China Ocean Acoustics (COA)*, Jan. 2016, pp. 1–4.

[60] M. D. Green, J. Rice *et al.*, "Channel-tolerant FH-MFSK acoustic signaling for undersea communications and networks," *IEEE Journal of Oceanic Engineering*, vol. 25, no. 1, pp. 28–39, 2000.

[61] Y. Yin, F. Zhou, G. Qiao, S. Liu, and Y. Yu, "Burst mode hybrid spread spectrum technology for covert acoustic communication," in *MTS/IEEE OCEANS*, Sep. 2013, pp. 1–8.

[62] W. Zhu, B. Daneshrad, J. Bhatia, and K. Hun-Seok, "MIMO systems for military communications," in *IEEE Military Communications Conference (MILCOMM)*, Washington, DC, Oct. 2006.

[63] T. Ahn, J. Jung, H. Sung, D. Lee, and T. Park, "Turbo equalization for covert communication in underwater channel," in *International Conference on Ubiquitous and Future Networks (ICUFN)*, Jul. 2016, pp. 462–464.

[64] S. Liu, G. Qiao, Y. Yu, L. Zhang, and T. Chen, "Biologically inspired covert underwater acoustic communication using high frequency dolphin clicks," in *MTS/IEEE OCEANS*, Sep. 2013, pp. 1–5.

[65] E. Calvo and M. Stojanovic, "Efficient channel-estimation-based multiuser detection for underwater CDMA systems," *IEEE Journal of Oceanic Engineering*, vol. 33, no. 4, pp. 502–512, Oct. 2008.

[66] M. A. B. Othman, J. Belz, and B. Farhang-Boroujeny, "Performance analysis of matched filter bank for detection of linear frequency modulated chirp signals," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 53, no. 1, pp. 41–54, Feb. 2017.

[67] R. Dillard and G. Dillard, *Detectability of Spread Spectrum Signals*. Norwood, USA: Atrech House, 1989.

[68] K. Kyouwoong, I. Akbar, K. Bae, and U. Jung-Sun, "Cyclostationary approaches to signal detection and classification in cognitive radio," in *IEEE symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Dublin, Ireland, Apr. 2007, pp. 212–215.

[69] G. Zhang, Y. Dong, and P. Liu, "Classification of low probability of interception communication signal modulations based on time-frequency analysis and artificial neural network," in *Conference on Electronics, Communications and Control (ICECC)*, Sep. 2011, pp. 1936–1939.

[70] G. D. Weeks, J. Townsend, and J. Freebersyser, "A method and metric for quantitatively defining low probability of detection," in *IEEE Military Communications Conference (MILCOMM)*, vol. 3, Dublin, Ireland, Oct. 1998, pp. 821–826.

[71] R. Diamant, L. Lampe, and E. Gamroth, "Low probability of detection for underwater acoustic communication," in *MTS/IEEE OCEANS*, St. Johns, Canada, Sep. 2014.

[72] M. Ainslie, P. Dahl, C. de Jong, and R. Laws, "Practical spreading laws: The snakes and ladders of shallow water acoustics," in *Proc. UA2014 - 2nd International Conference and Exhibition on Underwater Acoustics*, Rhodes, Greece, Jun. 2014, pp. 879–886.

[73] M. Porter *et al.*, "Bellhop code," Last time accessed: Nov. 2015. [Online]. Available: http://oalib.hlsresearch.com/Rays/index.html

[74] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen, and K. McCoy, "The JANUS underwater communications standard," in *Underwater Communications and Networking (UComms), 2014*. IEEE, 2014, pp. 1–4.

[75] J. G. Proakis, *Digital Communications*. New York, USA: 3rd ed. McGraw-Hill, 1995.

[76] C. R. Barnes and V. Tunnicliffe, "Building the world's first multi-node cabled ocean observatories (NEPTUNE Canada and VENUS, Canada): Science, realities, challenges and opportunities," in *MTS/IEEE OCEANS*, Kobe, Japan, 2008, pp. 1–8.