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Underwater Acoustic Sensor Networking Using Passive Phase Conjugation

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***Abstract*—Underwater acoustic sensor networks (UASNs) consist of sensors that are deployed to perform collaborative monitoring of tasks over a given volume of water. The quality of the underwater acoustic link is highly unpredictable, since it mainly depends on *fading* and *multipath*, which are not easily modeled phenomena. This is return severely degrades the performance at higher layers such as extremely long and variable propagation delays. In addition, this variation is generally larger in *horizontal* links than in *vertical* ones.**

In this paper, we analyze a modulation scheme and associated receiver algorithms. This receiver design take advantage of the *time reversal* (phase conjugation) and properties of spread spectrum sequences known as Gold sequences. This technique improves the signal-to-noise ratio (SNR) at the receiver and reduces the bit error rate (BER). We then applied the phase conjugation to the case of network communication. We show that this approach can give almost *zero* BER for a 2-hop communication compared to single hop. This link layer information can be used at the network layer to formalize routing decisions. We show these improvements by means of analytical analysis and simulations.
Keywords: Underwater acoustic sensor networks, time reversal, phase conjugation, analysis, simulations.

I. Introduction

Underwater acoustic sensors must be organized in an autonomous network that self-configures according to the varying characteristics of the ocean environment. Acoustic signaling for wireless digital communications in the sea environment can be a very attractive alternative to both radio telemetry and cabled systems. However, time-varying multipath and often harsh ambient noise conditions characterize the underwater acoustic channel, often making acoustic communications challenging. Major challenges in the design of underwater acoustic networks are: 1) The channel is severely impaired, mainly due to *multipath* and *fading*. 2) High bit error rates and temporary loss of connectivity mainly due to *shadowing*. 3) The *propagation delay* is five orders of magnitude higher than in radio frequency *terrestrial* channels and is usually variable. 4) Extremely low available *bandwidth and* limited *battery* energy at disposal.

In this paper, we present our analysis of a modulation scheme and associated receiver algorithms. They are much less complex than receivers using *adaptive* equalizers. We also present the quantification of SNR and BER gains using phase conjugation. We then applied the phase conjugation to the case of network communication. This link layer information can be used at the network layer to formalize routing decisions. In particular, it will allow a node to select its next hop with the aim of minimizing the energy consumption. This cross-layering improves the network lifetime of battery operated UASNs by reducing the number of retransmission attempts.

The organization of this paper is as follows. Section II details some interesting related work. In Section III, we shed light on the basic building blocks that contributed to the proposed solution. We present the receiver algorithms for single-hop point-to-point communication in Section IV. The performance analysis is provided in Section V. We applied the idea of phase conjugation on a linear network in Section VI. In Section VII, we conclude the paper and outline the future directions.

II. Related Work

Acoustic underwater communication is a challenging problem [9] for reliable high speed communication in the ocean. Underwater communication must deal with the inter-symbol interference (ISI) caused by the time-varying, dispersive, multipath shallow water environments, fading, noise and attenuation caused by the ocean which is considered as a bandwidth limited channel. The principle of time reversal (TR) , phase conjugation in frequency domain, can be used to overcome these challenges. TR has been investigated and applied widely as time reversal mirrors (TRMs) [1], [2] to solve such problems. Classically, TR is based on *spatial reciprocity* and *time symmetry* of the wave equation. TR is a process where a source at one location transmits sound which is received at another location, time reversed, and retransmitted. The retransmitted sound then focused back at the original source location. TR acoustic technologies were proven to be effective for acoustic focusing under unknown acoustic environmental conditions. The experiments in [1] showed that a TRM can produce significant focusing at long distances in a 125 m deep-water channel.

In [7], the authors experimentally demonstrated a way to simplify the study of TR in a fluctuating medium without invoking reciprocity in the propagation medium. This non reciprocity-based time reversal (NR-TR) is built from the forward propagation (or one-way propagation) between the TRM and the desired focal point. As a consequence, TR provides a good focus even when spatial reciprocity dose not hold in the medium. Instead of the TRM, a point-to-point (without arrays of sources or receivers) acoustic communication using passive

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phase conjugation (PPC) is investigated in [4] which use Gold codes to compensate the ISI problem. Gold codes are often used in the underwater acoustic community because of their autocorrelation properties [6], [8], [12], [13].

III. The Design Criteria

A. Gold Sequences

One important class of periodic sequences providing larger sets of sequences with good periodic cross-correlation is the class of Gold sequences. A set of Gold sequences can be constructed from any preferred pair of m-sequences which have a special three-valued cross-correlation function $\left\{-1+2^{[(L+2)/2]}, -1, -1-2^{[(L+2)/2]}\right\}$, where L is the length of a shift register. Any 2-register Gold code generator of length L can generate a set of $M = 2^L + 1$ sequences of length $N = 2^L - 1$ Gold sequences which are bipolar sequences with values -1 and 1. Their special property being any two different Gold sequences from the same family have very low cross-correlation values.

B. The Time reversal (phase conjugation) approach

The TR approach avoids the explicit *recovery* of the channel and its subsequent equalization via signal processing, and its associated algorithm complexity. To review how this focusing is achieved, we present here two configurations of active phase conjugation (APC) and passive phase conjugation (PPC) [4]. The channel impulse response (CIR) function is $h(t)$ and its Fourier transform is $H(\omega)$. Recall that, in the frequency domain, the convolution of $h(t)$ and transmit signal $s(t)$ is $H(\omega) S(\omega)$. Similarly, the correlation of two signals $s_1(t)$ and $s_2(t)$ is $S_1^*(\omega) S_2(\omega)$.

In APC configuration, the transmitter send a waveform $S(\omega)$ which travels through the channel and is recorded on the receiver as $H(\omega) S(\omega)$. The received waveform is phase conjugated $H(\omega)^* S(\omega)^*$, retransmitted through the same channel and is convolved again with $H(\omega)$ producing $|H|^2 S(\omega)^*$ at the original point. The term $|H|^2$ is the time reversal or phase conjugation *focusing* operator. In PPC configuration, the transmitter send two signals $S_1(\omega)$ and $S_2(\omega)$ one after another, respectively, through the same channel. They are received at the receiver as $H(\omega) S_1(\omega)$ and $H(\omega)\ S_2(\omega)$. The cross-correlation of $H(\omega) S_1(\omega)$ and $H(\omega) S_2(\omega)$ is the product $|H|^2 S_1^*(\omega) S_2(\omega)$ in which we find again the time reversal operator (TRO) $|H|^2$ which tends to re-concentrate or focus the multipath arrivals at zero time lag.

C. Underwater Propagation Model

1) Transmission Loss: In the underwater acoustic communication, the transmission loss (TL) describes how the acoustic *intensity* decreases as an acoustic *pressure* wave propagates outwards from a sound source. The $\mathrm{TL}(d,f)$ [dB] that a narrow-band acoustic signal centered at frequency f [KHz] experiences along a distance d [m] can described by the Urick propagation model [10],

$$\mathrm{TL}(d,f) = x \log d + \alpha(f) \cdot d + A. \tag{1}$$

where, the first terms account for geometric spreading, x is spreading coefficient, α is the medium absorption [dB/m] between $4°\mathrm{C}$ and $20°\mathrm{C}$, and A represents *transmission anomaly* and is measured in [dB]. The cylindrical spreading (horizontal radiation, spreading coefficient $x = 10$) characterizes shallow water communication and (1) provides the following approximation of the TL for cylindrical spread signals:

$$\mathrm{TL}(d,f) = 10 \log d + \alpha(f) \cdot d \times 10^{-3} \tag{2}$$

where d is the distance between the source and the hydrophone (receiver). Note that A is usually used to apply a spherical spreading model. Because the transmission anomaly is meant to account for the effects of *refraction* and is therefore not accounted in (2). More details can be found in [3] and [5].

2) the passive-sonar equation: Note that, the units of all sonar parameters are in [dB] and they are added together in forming the sonar equation. In the passive case, the target strength becomes irrelevant and one-way transmission is involved. Then the passive-sonar equation becomes

$$\mathrm{SL} - \mathrm{TL} = \mathrm{NL} - \mathrm{DI} + \mathrm{DT} \tag{3}$$

where SL is Source Level, NL is Noise Level, DI is (receiving) Directivity Index, and DT is Detection Threshold.

When the target is just being detected, the signal-to-noise ratio (SNR) equals to DT. An average value for the ambient noise level NL is 70 dB as a representative for the shallow water case. The directivity index DI is calculated based on the aperture of the antenna.

IV. Case I: Single-Hop Communication Framework

A receiver algorithm that we will use in this paper take advantage of TR (phase conjugation) and low cross-correlation of the Gold sequences. In PPC configuration, the message must be encoded in the correlation of the two consecutively transmitted waveforms S_1 and S_2. Encoding information in the correlation of two waveforms is not a *typical* signaling scheme and may provide some advantages. Therefore, we choose the PPC configuration for our underwater acoustic sensor network.

Our modulation cycles through a series of Gold sequences from the same family. With single receiver in acoustic communication using PPC, an ISI problem should be considered. To compensate for this, we rely upon families of Gold sequences to minimize the correlation between the sequences in each family.

A. Waveform design

Here G_i indicates the ith Gold sequence from a family of M sequences. When transmitted, each G_i is a bipolar sequence modulated by a carrier (BPSK modulation). The transmitted signal of a certain chip k $(1 \le k \le N)$ is

$$s_c(t) = g(k)\sqrt{E_c}\sqrt{\frac{2}{T_c}}\cos\left(2\pi f\left(t - kT_c\right) + \phi\right) \tag{4}$$

where $g(k)$'s are real numbers of k^{th} chip, ± 1 representations of a Gold sequence, E_c is the energy per chip, f is the carrier frequency, ϕ is the initial phase, and T_c is the chip duration.

Then the expressing of i^{th} Gold sequence in the duration NT_c is

$$G_i(t) = \sum_{k=0}^{N-1} g(k)\sqrt{E_i}\sqrt{\frac{2}{T_c}}\cos\left(2\pi f\left(t - kT_c\right) + \phi\right) \quad (5)$$

where E_i is the energy of i^{th} Gold sequence.

When $G_i(t)$ passes through underwater channel, the multipath signal will arrive at the receiver with different time delay. In communication system, the received signal is modeled as

$$\begin{aligned} r(t) &= \sum_p h_p G_i\left(t - \tau_p\right) + N_o(t) \\ &= \sum_p h_p G_i(t) \otimes \delta\left(t - \tau_p\right) + N_o(t) \end{aligned} \quad (6)$$

where τ_p is the delay of p^{th} path, h_p is considered as p^{th} CIR and N_o is the ambient noise of channel. Because PPC is an approach in the frequency domain, Fourier transform of (6) is

$$R(\omega) = H(\omega)\, G_i(\omega) + N_o(\omega) \quad (7)$$

B. Pulse position modulation (PPC-PPM)

Pulse position modulation is implemented to take advantage of PPC, we set the first signal transmitted S_1 as the reference Gold sequences $\{G_i, 1 \leq i \leq M\}$ with a constant time interval between them as shown in Fig. 1. If this constant interval can be divided into K resolvable time slots, each pair of G_i's will carry $\log_2 K$ bits of information. The second signal S_2 (black) is the repeat of the $\{G_i\}$ (blue) with a *purposely* varying distance between the reference and second positions in order to convey the information bits being transmitted.

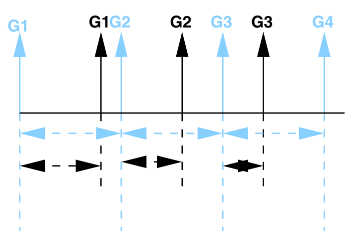

Fig. 1. Waveform Design for PPC-PPM

At the receiver, the particular order of the Gold sequences being transmitted is known, so the appropriate matched filter tuned to G_i can be applied to each received symbol. We can illustrate this scheme as following:

$$\{G_i(\omega)\} \longrightarrow H(\omega)\{G_i(\omega)\} \xrightarrow{\text{filter } G_i} H(\omega)|G_i|^2$$
$$\{G_i(\omega - \varphi_i)\} \longrightarrow H(\omega)\{G_i(\omega - \varphi_i)\} \xrightarrow{\text{filter } G_i} H(\omega)|G_i(\varphi_i)|^2$$

where φ_i is the phase difference.

When symbols overlap due to multipath, the low cross-correlation property of the Gold sequences ensures that the different matched filters *do not* let through much of the interfering symbols. Then it is possible to decode the information from relative positions of the dominant arrivals only.

The correlation of the two matched filter outputs is

$$\left\langle H(\omega)|G_i|^2, H(\omega)|G_i(\varphi_i)|^2 \right\rangle = |H|^2 |G_i|^2 |G_i(\varphi_i)|^2 \quad (8)$$

and the resulting waveform is proportional to $|H|^2$. The auto-correlation function of the multipath impulse response, Γ_h, is defined as following

$$\Gamma_h(0) = \int_0^{NT_c} |h(t)|^2\, dt = \int_0^{\frac{1}{NT_c}} |H(\omega)|^2\, d\omega \quad (9)$$

where the duration of codewords N is much greater than the multipath channel spread intervals.

C. Calculation of SNR and BER

In this Section, we discuss the calculation of signal-to-noise ratio (SNR) and bit-error rate (BER) that quantifies the robustness of our approach to the presence of external noise.

1) Signal-to-Noise-Ratio (SNR): The transmitted signals are set to be ± 1 pulses controlled by the generated sequence of length N. The total transmitted signal energy per Gold sequence

$$E_t = \frac{1}{T_c}\int_0^{NT_c} s_c^*(t)\, s_c(t)\, dt \quad (10)$$

is N per path because $s_c(t)$ was normalized to unit power ($E_c = 1$). The total received signal energy E_r over all multipaths is

$$E_r = \Gamma_h(0)\, E_t = \Gamma_h(0) \cdot N \cdot m \quad (11)$$

where m is the number of Gold sequences used to construct PPM, $1 \leq m \leq M$.

The output of the correlator $y(k)$ at k^{th} chip received can be written as

$$y(k) = \Gamma_h(0)\, |G_i|^2 \, |G_i(\varphi_i)|^2 + n(k) \quad (12)$$

where $n(k)$ is the noise output and can be developed from (6). Substitute (5) into (6), we find that beside the desired component $\sqrt{E_c}$, there are still two undesired components which indicate the interferences from multipath and ambient noise, I_{mp} and I_{no} respectively. Due to the independence of each chip in pseudorandom noise (PN) code, the first order statistics of I_{mp} and I_{no} will be zero and their variances can be expressed as

$$V_{mp}(k) = E_c \sum_p h_p^2 cos\left(\phi'(p)\right)$$
$$V_{no}(k) = \frac{N_0}{2}$$

Then, we have the variance of $n(k)$as following

$$V_n(k) = V_{mp}(k) + V_{no}(k)$$

The received SNR is then expressed as

$$\frac{E_r}{I_o} = \frac{\Gamma_h(0).N.m}{N.V_n(k)} = \frac{\Gamma_h(0).m}{E_c \sum_p h_p^2 cos\left(\phi'(p)\right) + \frac{N_0}{2}} \quad (13)$$

The bit energy SNR is

$$\frac{E_b}{I_o} = \frac{1}{\log_2 K} \cdot \frac{E_r}{I_0} \quad (14)$$

where each code word carries $\log_2 K$ bits of information.

2) Bit-Error-Rate (BER): The classic BER of BPSK in multipath fading channel can be calculated as

$$\text{BER} = f\left(\frac{E_b}{N_o}\right) \tag{15}$$

where $f(\cdot)$ is the bit-error function which is developed from the conditional error function for the binary case. More details can be found in [11].

Therefore, the calculation of the BER in our model can be expressed as a function of the ratio between the energy of received bit and the noise at the receiver. While r [bps] is the considered bit rate, the energy of received bit can be calculated by $P_{i_{max}} \cdot 2N/(r \cdot TL)$, where $P_{i_{max}}$ is the maximum transmitting power for node i, and $2N$ is the gain from pulse compression (for detail, see (12)). We recall the (3) in the section III-C for the application of our PPC-PPM construction, SL relates to the transmitted signal intensity at 1 m from the source according to the following expression:

$$SL = \frac{E_b}{N_o} + 2TL + 70 - DI = 10\log\frac{I_t}{1\mu Pa} \tag{16}$$

where I_t is in μPa. Solving for I_t yields:

$$I_t = 10^{SL/10} \times 0.67 \times 10^{-18} \tag{17}$$

in $Watts/m^2$. Finally, the transmitter power needed to achieve an intensity I_t at a distance of 1 m from the source in the direction of the receiver is expressed as

$$P_t = 2\pi \times 1m \times h \times I_t \tag{18}$$

in $Watts$, where h is the water depth in m.

Then the maximum transmitting power $P_{i_{max}}$ for node i is equal to P_t which is calculated from the TL, considered as the maximum allowable one-way transmission loss in passive sonars. The BER is then finally expressed as

$$BER = f\left(\frac{P_{i_{max}} \cdot 2N}{N_o \cdot r \cdot TL}\right) \tag{19}$$

V. Simulation Results

The PPC-PPM performance is tested using Matlab-Simulink. A set of Gold sequence will be generated and pulse positioned in order to encode the bit information. We use the BPSK carrier at 3.5 kHz to modulate the codewords and then send them through the multipath fading channel. At the reception, the signal received is passed through a matched filter tuned to G_i. We then perform the correlation of the matched filter outputs to implicitly autocorrelate the CIR H by which each of the two G_i receptions have been spread, realizing a filter consisting of the TR (phase conjugation) operator $|H|^2$ as discussed in Section 3.2.

For the simulations, we first consider the communication between two nodes in the shallow water. One node works as transmitter, the other as receiver, and both are centered at 3.5 kHz and have a bandwidth of 500 Hz. The Fig. 2 show the classical (theoretical) BER (15) and PPC-PPM BER (19) for underwater multipath fading channel (for $r = 126$ [bps] and 500 [bps], respectively). The distance between the two nodes, in both cases, is 1 km at depth 50 m. The results from our simulations for PPC-PPM BER gives better performance compared to the theoretical results. This shows that the PPC-PPM scheme can provide promising results for the low SNR region. Further, it is also immediately clear that the PPC-PPM BER using a lower value of r (i.e., 126 [bps] in Fig. 2) gives better results compared to higher values (i.e., 500 [bps] in Fig. 2). For details on this behavior, see (19).

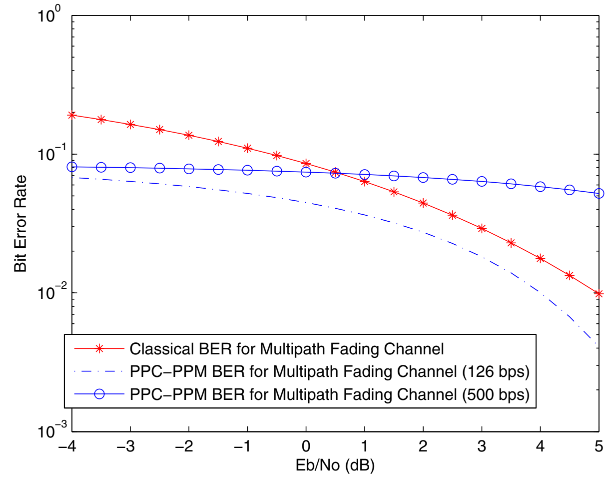

Fig. 2. Bit-Error-Rate vs. SNR for 126 [bps] and 500 [bps]

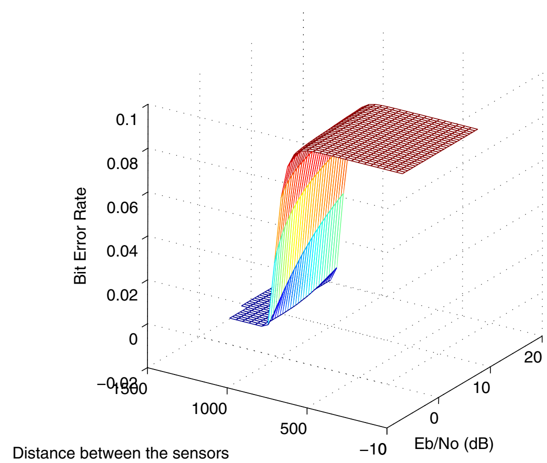

Fig. 3. Bit-Error-Rate vs. Distance

Fig. 3 shows the BER w.r.t distance for $r = 126$ [bps] and h = 50 m. It is evident from the figure that the value of PPC-PPM BER decreases with distance. This behavior is also clear from (19), i.e., when the distance is increased, the TL will increase (see (2)) but it will decrease the BER.

VI. Case II: Multi-Hop Communication Framework

A Three-Node Linear Network: We take an example of linear 3-node network. The node 1 (source) sends a signal to node3 (destination), which is 2-hop away and is relayed by node

2 which can hear both 1 and 3. In the one-way transmission PPC-configuration as shown in Fig. 4, the first-transmitter send two signals $S_1(\omega)$ and $S_2(\omega)$ one after another, respectively, through the same channel. They are received at the first-receiver as $H(\omega)\,S_1(\omega)$ and $H(\omega)\,S_2(\omega)$. The cross-correlation of $H(\omega)\,S_1(\omega)$ and $H(\omega)\,S_2(\omega)$ is the product $|H|^2\,S_1^*(\omega)$ $S_2(\omega)$ in which we find the time reversal operator (TRO). The autocorrelation of the CIR $|H|^2$ tends to re-concentrate or focus the multipath arrivals at zero time lag. We take the information bits out of the correlation of two waveforms in order to continue the next transmission. Then, these bits are used to reconstruct the new Gold sequences $S_1^{'} = S_1^* S_2$ and $S_2^{'} = (S_1^* S_2)(\varphi) = S_1^* S_2 e^{-j\frac{\varphi}{2\pi}}$ such that the precedent bits in between the reference and second position (as explained in Section IV-B) are replaced by the bits we decoded from the first reception. Afterwards, the transmission from node 2 to node 3 using exactly the same PPC-PPM, we find almost zero BER at the node 3 as shown in Fig. 4. We explain this behavior in the following proof.

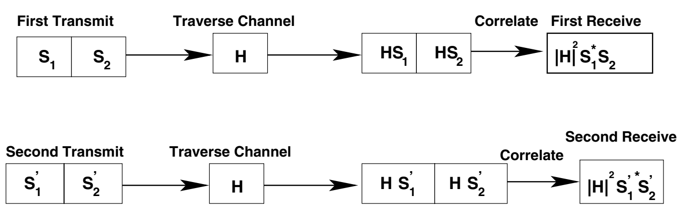

Fig. 4. Passive Phase Conjugation (PPC) in a 3-node Network

Proof: For the first transmission-reception pair as shown in Fig. 4, if $S_1 = S(\omega)$ and $S_2 = S(\omega)\,e^{-j\frac{\varphi}{2\pi}}$, where φ is the phase difference. Then

$$Corr\,(HS_1, HS_2) = \int_{-\infty}^{+\infty} (H(\omega)\,S(\omega))^* \; H(\omega)\,S(\omega)\,e^{-j\frac{\varphi}{2\pi}}d\omega = |H(\omega)|^2\,|S(\omega)|^2\,e^{-j\frac{\varphi}{2\pi}}$$

And for the 2^{nd} transmission-reception pair as shown in Fig. 4, we have

$$Corr\left(HS_1^{'}, HS_2^{'}\right) = \int_{-\infty}^{+\infty} (HS_1^* S_2)^*\,H\,(S_1^* S_2)(\varphi)\,d\omega$$

$$= \int_{-\infty}^{+\infty} |S(\omega)|^2\,e^{j\frac{\varphi}{2\pi}} H^*(\omega)\,H(\omega)\,|S(\omega)|^2\,e^{-j\frac{\varphi}{\pi}}d\omega$$

$$= |S(\omega)|^4 \left(\int_{-\infty}^{+\infty} H^*(\omega)\,H(\omega)\,d\omega\right) e^{-j\frac{\varphi}{2\pi}}$$

$$= |H(\omega)|^2\,|S(\omega)|^4\,e^{-j\frac{\varphi}{2\pi}}$$

The proof is complete.

VII. Conclusions and Future Work

The TR focus enables the underwater sensor network to minimize the effect of multipath and channel fading thus improving the SNR and reducing the BER and ISI. PPC implicitly equalizes the channel by refocusing channel spread. We have quantified the gain of PPC temporal compression, in a single-hop point-to-point setup, using Gold sequences to implement receivers based on PPM modulation schemes. We have also shown that PPC-PPM can be applied to a network to achieve almost *zero* BER for a 2-hop communication compared to single hop. We have shown that with the help of a proof. This result can be of significant importance in making routing decisions for underwater acoustic sensor networks. In particular, it allows a node to select its next hop with the aim of minimizing the energy consumption. This cross-layering will improve the network lifetime of battery operated underwater acoustic sensor networks by selecting a 2-hop communication mode compared to one-hop (where applicable) and reducing the number of retransmission attempts between any given pair of nodes.

In future, we will consider a multihop 3D underwater acoustic sensor network and extend the results of this paper to formalize an *optimal* distributed routing algorithm with the aim of minimizing energy consumption per successful transmission and maximizing the network lifetime.

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