A Multimedia Cross-Layer Protocol for Underwater Acoustic Sensor Networks

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***Abstract*—Underwater multimedia acoustic sensor networks will enable new underwater applications such as multimedia coastal and tactical surveillance, undersea explorations, picture and video acquisition and classification, and disaster prevention. Because of the different application requirements, there is a need to provide differentiated-service support to delay-sensitive and delay-tolerant data traffic as well as to loss-sensitive and loss-tolerant traffic. While research on underwater communication protocol design so far has followed the traditional layered approach originally developed for wired networks, improved performance can be obtained with a cross-layer design. Hence, the objective of this work is twofold: 1) study the interactions of key underwater communication functionalities such as modulation, forward error correction, medium access control, and routing; and 2) develop a distributed cross-layer communication solution that allows multiple devices to *efficiently* and *fairly* share the bandwidth-limited high-delay underwater acoustic medium.**

***Index Terms*—Underwater wireless communications, underwater sensor networks, cross-layer routing and MAC algorithms, optimization.**

I. Introduction

UNDERWATER Acoustic Sensor Networks (UW-ASNs) [1] consist of sensors deployed to perform collaborative monitoring tasks over a body of water. UW-ASNs enable applications for oceanographic data collection, pollution monitoring, offshore exploration, and assisted navigation. Wireless acoustic communication is the typical physical layer technology in underwater networks because of the propagation limitation of radio frequency and optical waves [2]. A significant surge in research on underwater sensor networks in the last few years has resulted in increased interest in the networking community for this leading-edge technology. This growing interest can be largely attributed to new applications enabled by networks of small devices capable of harvesting information from the underwater physical environment, performing simple processing on the extracted data, and transmitting it to remote locations. Several architectures, protocols, and solutions for underwater networking have been proposed in [3], [4], [5], [6]. As of today, however, existing works on UW-ASNs are mostly focused on enabling the measurement of scalar physical phenomena like temperature, water salinity, and presence of contaminants/pollutants in water. Furthermore, most of these applications have in general very low bandwidth demands and are usually delay tolerant.

In order to enable new applications such as multimedia coastal and tactical surveillance, undersea explorations, picture and video acquisition and classification, and disaster prevention, underwater sensor networks will need to be able to retrieve multimedia data originated from heterogeneous sources, and store, process, and fuse it while it is being transmitted. Many of the above applications, however, require the underwater sensor network paradigm to be re-thought in view of the need for mechanisms to deliver multimedia content with a certain level of Quality of Service (QoS). As a matter of fact, mechanisms to efficiently meet application-level QoS requirements, and to map them into network-layer metrics such as end-to-end delay, delay jitter, and packet error rate, have not been primary concerns in mainstream research on underwater sensor networks.

There are several characteristics of UW-ASNs that make QoS delivery of multimedia content a challenging task such as frequency-dependent transmission loss, colored noise, multipath, Doppler frequency spread, high propagation delay, sensor battery and resource constraints, variable channel capacity, and cross-layer coupling of functionalities [1], [7]. In multihop wireless networks, in fact, there is a strict interdependence among functions handled at all layers of the communication stack. Hence, the various functionalities aimed at QoS provisioning should not be designed separately when efficient solutions are sought. While most of research on underwater communication protocol design so far has followed the traditional layered approach, which was originally developed for wired networks, improved performance in wireless networks can be obtained with a cross-layer design [8], [9], especially in a harsh environment such as the underwater.

Given our research experience in this area, we claim that UW-ASNs require for a cross-layer communication solution to allow for an efficient use of the scarce resources such as bandwidth and battery energy. However, although we advocate integrating *highly specialized* communication functionalities to improve network performance and to avoid *duplication of functions* by means of cross-layer design, it is important to consider the ease of design by following a *modular design approach*. This will also allow improving and upgrading particular functionalities without the need to re-design the entire communication system. Cross-layer interactions need to be thoroughly studied and controlled, and no cross-layer dependency should be left unintended as this may lead to poor system performance [10], [11].

For these reasons, we rely on the above-mentioned design guidelines and propose a cross-layer communication solution

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for UW-ASN multimedia applications that is built upon our previous work on underwater routing [3] and Medium Access Control (MAC) [4] protocols. In particular, the objective of our work is twofold: 1) explore the interaction of key underwater communication functionalities such as modulation, Forward Error Correction (FEC), MAC, and routing; 2) develop a distributed cross-layer solution integrating highly specialized communication functionalities that cooperate to allow multiple devices to *efficiently* and *fairly* share the bandwidth-limited high-delay underwater acoustic medium.

To the best of our knowledge, this work is the first to propose a coherent cross-layer framework to optimize communications in UW-ASNs. The remainder of this article is organized as follows. In Sect. II, we describe our design philosophy for cross-layering and we introduce our communication solution. In Sect. III, we analyze the performance results. Finally, in Sect. IV, we draw the main conclusions and outline future research directions.

II. Cross-layer Communication Solution

A. Our Cross-layer Design Approach

Three approaches to cross-layer design are possible:

Pairwise interactions (e.g., [9], [12]). Resource allocation problems are treated by considering simple interactions between two communication layers. A typical example is the interaction between the congestion control and power control mechanisms [9]; another is the joint power control and scheduling problem, which is addressed in [12]. This approach does not take into account the tight coupling among functionalities handled at all layers of the protocol stack typical of multi-hop underwater networks.

Heuristic approaches (e.g., [13]). Resource allocation problems following this approach consider interactions between several communication functionalities at different layers as it is not always possible to model and control the interactions between functionalities; solutions in these category rely on heuristics, which often lead to suboptimal performance.

Resource allocation frameworks (e.g., [8], [14]). These approaches integrate different communication functionalities into a coherent mathematical framework and provide a unified foundation for cross-layer design and control in multi-hop wireless networks. Solutions in this category try to reach optimality based on an application-dependent objective function, and provide guidelines and tools to develop mathematically sound distributed solutions.

In our work, we follow this last design approach. Our objective is to develop a *resource allocation framework* that accurately models every aspect of the layered network architecture, resulting in theoretical and practical impacts beyond the previously established results. By exploiting our previous experience in modeling underwater communication functionalities, we develop a *highly specialized cross-layer communication solution* that can adapt to different application requirements and seek optimality in several different situations. Our solution relies on a distributed optimization problem to jointly control the *routing*, *MAC*, and *physical functionalities* in order to achieve efficient communications in the underwater environment. In particular, the proposed solution combines a 3D geographical routing algorithm (*routing functionality*), a novel hybrid distributed CDMA/ALOHA-based scheme to access the bandwidth-limited high-delay shared acoustic medium (*MAC functionality*), and an optimized solution for the *joint* selection of modulation, FEC, and transmit power (*physical functionalities*). The proposed solution is tailored for the characteristics of the underwater acoustic physical channel, e.g., it takes into account the very high propagation delay, which may vary in horizontal and vertical links due to multipath, the different components of the transmission loss, the impairment of the channel, the scarce and range-dependent bandwidth, the high bit error rate, and the limited battery capacity. These characteristics lead to very low utilization efficiencies of the underwater acoustic channel and high energy consumptions when common MAC and routing protocols are adopted in this environment, as thoroughly analyzed in [3], [4].

The remainder of this section is organized as follows. In Sect. II-B, we group underwater multimedia applications into four traffic classes and highlight their different requirements. In Sect. II-C, we analyze the acoustic channel transmission loss, available bandwidth, noise structure, and maximum capacity, and describe the main physical layer functionalities dealt with in this work. In Sect. II-D, we present possible modulation and FEC techniques suitable for the underwater environment, and evaluate their performance. In Sect. II-E, we introduce the CDMA/ALOHA-based MAC and location-based routing functionalities, which are the core of our cross-layer solution, and we discuss how to integrate and control different communication functionalities in a distributed manner. Finally, in Sect. II-F, we detail the protocol operation. While we present the different functionalities in isolation for the sake of presentation clarity, the last sections focus on their coherent cross-layer integration.

B. Multimedia Traffic Classes

We envision that underwater multimedia sensor networks will need to provide support and differentiated service to applications with different QoS requirements, ranging from delay sensitive to delay tolerant, and from loss sensitive to loss tolerant. Hence, we consider the following four traffic classes:

Class I (delay-tolerant, loss-tolerant). It may include multimedia streams that, being intended for storage or subsequent offline processing, do not need to be delivered within strict delay bounds. This class may also include scalar environmental data or non time-critical multimedia content such as snapshots.

Class II (delay-tolerant, loss-sensitive). It may include data from critical monitoring processes that require some form of offline post processing.

Class III (delay-sensitive, loss-tolerant). It may include video/ audio multi-level streams as well as meta-data associated with the stream that need to be delivered within strict delay bounds and that are, however, relatively loss tolerant (e.g., video streams can be within a certain level of distortion). This class may also include monitoring data from densely deployed scalar sensors whose monitored phenomenon is characterized by high temporal/spatial correlation, or loss-tolerant snapshots of a phenomenon taken from several multiple viewpoints.

Class IV (delay-sensitive, loss-sensitive). This class may include data from time-critical monitoring processes such as distributed control applications.

C. Physical Layer Functionalities

The underwater transmission loss describes how the acoustic intensity decreases as an acoustic pressure wave propagates outwards from a sound source. The transmission loss $TL(d, f_0)$ [dB] that a narrow-band acoustic signal centered at frequency f_0 [kHz] experiences along a distance d [m] can be described by the Urick propagation model [15],

$$TL(d, f_0) = \chi \cdot 10 \log_{10}(d) + \alpha(f_0) \cdot d. \quad (1)$$

In (1), the first term accounts for *geometric spreading*[1], which refers to the spreading of sound energy caused by the expansion of the wavefronts. It increases with the propagation distance and is independent of frequency. The second term accounts for *medium absorption*, where $\alpha(f_0)$ [dB/m] represents an absorption coefficient that describes the dependency of the transmission loss on the central frequency f_0.

Interestingly, the transmission loss increases not only with the transmission distance but also with the signal frequency. As a result, given a maximum tolerated transmission loss TL_{max} [dB], which depends on the transmitter output power and the receiver sensitivity, a maximum central frequency exists for each range. In addition, because of the colored structure of the underwater ambient noise *power spectrum density (p.s.d.)*, $N(f)$ [W/Hz] or [$\mathrm{dB_{re\,\mu Pa}}$/Hz][2], the useful acoustic bandwidth B [kHz][3] depends on the transmission distance and on the central frequency. Hence, the design of the routing and MAC functionalities of our cross-layer solution (Sect. II-E) takes this characteristic of the underwater channel into account, which can be stated as follows: *a greater throughput may be achieved if data packets are relayed over multiple shorter hops instead of being transmitted over one long hop.*

Moreover, the unique *'V' structure* of the underwater acoustic noise p.s.d. (which has a minimum of 20 $\mathrm{dB_{re\,\mu Pa}}$/Hz at about 40 kHz), makes *non trivial* the choice of the optimal bandwidth. Interestingly, when the central frequency is low, e.g., $f_0 = 10$ kHz, a higher relative Signal-to-Noise-Ratio (SNR) is achieved with a narrow bandwidth ($B = 3$ as opposed to 9 kHz); conversely, when the central frequency is high, e.g., $f_0 = 100$ kHz, a higher relative SNR is achieved with a wide bandwidth ($B = 90$ as opposed to 30 kHz). This implies that if a high central frequency is selected, a large bandwidth can be used for communication, although a high transmit power would be needed to compensate for the higher transmission loss. Our communication solution takes into account this unique characteristic, which is caused by the peculiar 'V' structure of the noise p.s.d. and by the fact that the difference between the slopes of $N(f)$ and $TL(d, f)$ decreases as the central frequency increases (e.g., positive for low frequencies and negative for high ones).

In [7], the author assesses the bandwidth dependency on the distance using an information-theoretic approach that takes into account the underwater propagation loss and ambient noise. The author defines the bandwidth corresponding to optimal signal energy allocation as the one that maximizes the channel link capacity. However, in order to find the optimal signal power distribution across the chosen band an a priori knowledge of the optimal SNR threshold (SNR_{th}) at the receiver is required, which is often a non-realistic assumption in practical systems. In [7], a heuristically pre-specified value of 20 dB is suggested for this threshold.

If we denote by $S(d, f)$ [W/Hz] the p.s.d. of the transmitted signal chosen for a distance d, i.e., the power distribution across the chosen band $< f_0(d), B(d) >$, the total transmitted power is $P(d) = \int_{<f_0(d),B(d)>} S(d, f)df$ and the signal to noise ratio is,

$$SNR(d, B(d)) = \frac{\int_{<f_0(d),B(d)>} S(d, f) \cdot TL(d, f)^{-1} df}{\int_{<f_0(d),B(d)>} N(f)df}. \quad (2)$$

By assuming that the noise is Gaussian and that the channel is time-invariant for some interval time, the channel transfer function appears frequency-nonselective in a narrow sub-band Δf centered around frequency f_i in which the noise can be approximated as white (with p.s.d. $N(f_i)$). Under these assumptions, the capacity C [bps] is given by,

$$C(d) = \sum_i \Delta f \log_2 \left[1 + \frac{S(d, f_i) \cdot TL(d, f_i)^{-1}}{N(f_i)} \right]. \quad (3)$$

According to the *water-filling principle* [16], maximizing the capacity with respect to $S(d, f)$, *subject to the constraint that the transmitted power be finite*, yields to the optimal p.s.d $S(d, f) = K(d) - N(f) \cdot TL(d, f)$, $f \in < f_0(d), B(d) >$, where $K(d)$ [W/Hz] is a distance-dependent constant. The SNR corresponding to this optimal power distribution is thus given by,

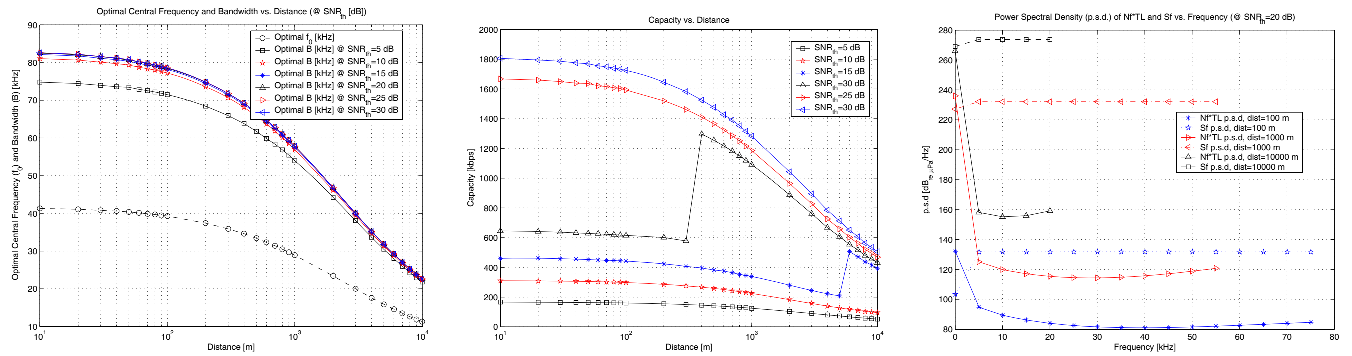
$$SNR(d, B(d)) = K(d) \frac{\int_{<f_0(d),B(d)>} TL(d, f)^{-1} df}{\int_{<f_0(d),B(d)>} N(f)df} - 1. \quad (4)$$

Figure 1(a) depicts the chosen central frequency f_0 and bandwidth B, while Fig. 1(b) shows the associated theoretical capacity C when the fixed pre-specified target SNR_{th} ranges in $[5, 30]$ dB. Note that, while the optimal central frequency f_0 (lower curve in Fig. 1(a)) is independent on the target SNR_{th}, both the chosen bandwidth B and maximum theoretical capacity C depend on it. Consequently, fixing the SNR at the receiver makes their values *suboptimal*: hence, the words 'optimal' and 'chosen'. Figure 1(c) depicts the p.s.d. of $N(f) \cdot TL(d, f)$ and $S(d, f)$, as well as the signal band occupancy, when the pre-specified target SNR_{th} is *heuristically* set to 20 dB, as suggested in [7]. This shows that, if the receiver SNR is not considered in the link optimization at the sender side, suboptimal decisions are taken. In fact, the link (and thus the overall system) performance strongly depends on

[1]There are two kinds of geometric spreading: *spherical* (omni-directional point source, spreading coefficient $\chi = 2$) and *cylindrical* (horizontal radiation only, spreading coefficient $\chi = 1$).

[2]A reference pressure of $1\mu Pa$ is used to express acoustic source levels in $dB_{re\,\mu Pa}$. Hence, 1 and 10 W correspond to 171 and 181 $\mathrm{dB_{re\,\mu Pa}}$.

[3]We assume the band to be symmetrical around the central frequency, i.e., the band occupancy of bandwidth B at central frequency f_0 is $[f_0 - B/2, f_0 + B/2]$, which for convenience will be denoted as $< f_0, B >$.



(a) (b) (c)

Fig. 1. (a): Optimal central frequency f_0 [kHz] and chosen bandwidth B [kHz] vs. distance d [m], given a fixed *pre-specified* target $SNR_{th} \in [5, 30]$ dB; (b): Chosen capacity C [kbps] vs. distance d [m], given a fixed *pre-specified* target $SNR_{th} \in [5, 30]$ dB; (c): P.s.d. of $N(f) \cdot TL(d, f)$ and $S(d, f)$ [$\text{dB}_{\text{re}\,\mu\text{Pa}}/\text{Hz}$] vs. frequency f [kHz] at $d = 10^2, 10^3, 10^4$ m when the *pre-specified* target SNR_{th} is *heuristically* set to 20 dB.

the selected SNR_{th}, as it is clear from Figs. 1 and 2(a).[4] For these reasons, our cross-layer solution *jointly controls* physical transmission, modulation, and FEC functionalities in such a way as to optimize the overall system performance, i.e., either by minimizing the *energy per successfully received bit* or by maximizing the *net bit rate*. Among these objective functions, the cross-layer solution will choose depending on the application requirements.

In the next sections, we present the main communication functionalities of our cross-layer solution. Without relying on a pre-specified SNR_{th}, our algorithm jointly selects, in a distributed manner, the optimal p.s.d. of the transmitted signal, i.e., K, f_0, and B, and the best combination of modulation and FEC techniques as well as MAC and routing, with the objective of either saving energy, thus prolonging the lifetime of the network in most scenarios[5] (*Objective 1*), or maximizing the network end-to-end throughput (*Objective 2*), thus increasing the system performance. The actual objective (1 or 2) would depend on the specific application requirements that need to be met, and is either decided *offline* during the deployment phase or *online* through control signaling from the surface station. In order to achieve the selected objective, our cross-layer solution interfaces with the modulation functionality by choosing the optimal transmitted power and number of bits per symbol, thus trading *power efficiency* for *spectral efficiency*[6]. Moreover, our solution interfaces with the *FEC functionality* and trades channel coding overhead, i.e., the amount of redundancy introduced to protect the transmission, for the level of protection from noise interference, i.e., the bit error correcting capability at the receiver (Sect. II-D). Last, but not least, our solution jointly decides on the best next hop (*routing functionality*) and how/when to access the channel and send the data to the chosen next hop (*MAC functionality*) (Sect. II-E).

D. Modulation and FEC Interactions

We consider several classes of modulation schemes suitable for underwater communications such as PSK, FSK, and QAM (both in their coherent and non-coherent versions), whose Bit Error Rate (BER) vs. SNR performance is reported in Fig. 2(b). Note that, while BER plots usually refer to the received bit SNR, i.e., E_b/N_0, we define the p.s.d. of an equivalent white noise as $N_0 = (1/B) \cdot \int_{<f_0,B>} N(f) df$ and the received bit energy as $E_b = (1/C) \cdot \int_{<f_0,B>} S(d, f) \cdot TL(d, f)^{-1} df$. Hence, the equivalent bit SNR is $E_b/N_0 = (B/C) \cdot SNR$.

As far as the FEC functionality is concerned, we consider block codes because of their energy efficiency and lower complexity compared to convolutional codes [17], [18]. In fact, the limited energy-consumption requirements of UW-ASNs calls for energy-efficient low-complexity error control coding schemes. In [18], the energy consumption profile of convolutional codes is presented based on a μ-AMPS architecture. It is shown that no convolutional code provides better energy efficiency for $BER > 10^{-5}$ than uncoded transmission [18]. Similarly, in [17], convolutional and BCH (Bose, Ray-Chaudhuri, Hocquenghem)[7] codes are compared in terms of energy efficiency in a framework to optimize the packet size in wireless sensor networks. Results of this work reveal that BCH codes outperform the most energy-efficient convolutional code by almost 15%. Consequently, we do not consider convolutional codes in our work. Our framework, however, can be extended to support convolutional codes as well as other codes such as turbo codes or Type I or II Automatic Repeat reQuest (ARQ) schemes.

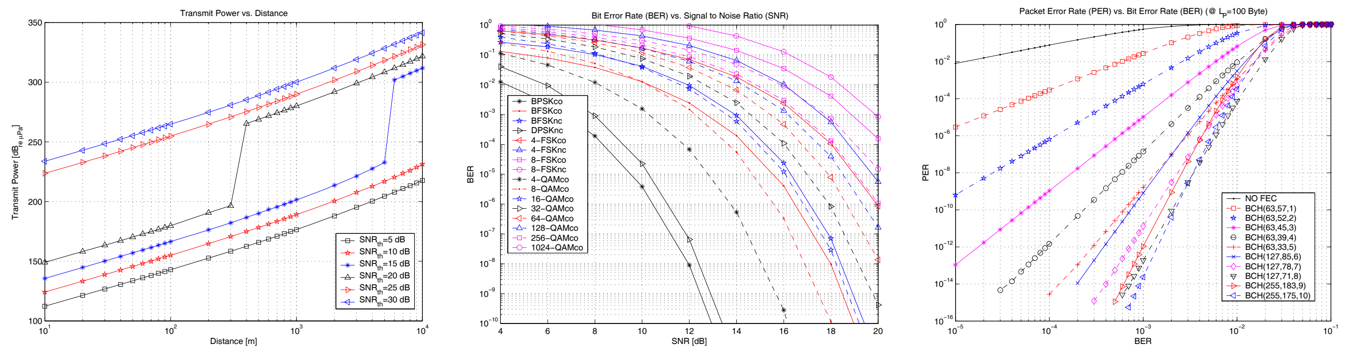
A BCH block code is represented by (n, k, t), where n is the block length, k is the payload length, and t is the error correcting capability in bits. In our experiments, we used BCH codes able to correct up to $t = 10$ bit errors. Figure 2(c) depicts PER vs. BER for different BCH(n,k,t) codes and for

[4] The discontinuity of the capacity as well as of the transmitted power in Figs. 1(b) and 2(a) at 300 and 5000 m, respectively, is caused by the minimum frequency $f_0 - B/2$ reaching zero. Consequently, because of the constraint on the band symmetry around the central frequency, the maximum frequency reaches $f_0 + B/2$.

[5] In the case of inhomogeneous network densities, network topologies with different node degrees, and asymmetric traffic patterns the maximization of the network lifetime should be achieved not only through 'energy minimization' but also through 'load balancing'.

[6] By moving to a higher-order constellation, it is possible to transmit more bits per symbol using the same bandwidth (*higher spectral efficiency*), although at the price of higher energy per bit required for a target Bit Error Rate (BER) (*lower power efficiency*).

[7] A BCH code is a multilevel, cyclic, error-correcting, variable-length digital code used to correct multiple random error patterns.



(a) (b) (c)

Fig. 2. (a): Transmit power P $[\mathrm{dB}_{\mathrm{re}\,\mu\mathrm{Pa}}]$ vs. distance d [m], given a fixed *pre-specified* target $SNR_{th} \in [5, 30]$ dB; (b): Bit Error Rate (BER) vs. SNR for different coherent and non-coherent typical underwater modulation techniques; (c): Packet Error Rate (PER) vs. BER for different BCH(n,k,t) codes.

the case of uncoded transmissions (NO FEC) computed as,

$$\begin{cases} BLER(n,k,t) = \sum_{i=t+1}^{n} \binom{n}{i} BER^i \cdot (1 - BER)^{n-i} \\ PER(L_P, n, k, t) = 1 - \left[1 - BLER(n,k,t)\right]^{\left\lceil \frac{L_P}{k} \right\rceil}, \end{cases} \tag{5}$$

where BLER represents the BLock Error Rate and L_P is the packet length, which is set to 100 Byte.

To qualitatively understand how we capture the cross-layer interactions between the modulation and FEC functionalities to improve the link performance, let us consider the objective of these functionalities when they operate in isolation. The FEC functionality performs the so-called *channel coding*, i.e., introduces some controlled bit redundancy with the objective of reducing the PER at the receiver given a certain BER on the link. On the other hand, the modulation functionality decides what the best modulation scheme and its constellation should be either i) to maximize the link raw rate, i.e., the rate of transmitted bits (*high spectrum efficiency*), or ii) to minimize the link BER (*high power efficiency*). It is clear that improved performance can be achieved by jointly selecting the BCH code and the modulation scheme. Hence, our cross-layer design is aimed at maximizing the *link net rate*, i.e., the rate of *successfully* received bits, by jointly deciding: 1) the modulation scheme and its constellation (which affect the link raw rate), 2) the transmit power (which affects the BER), and 3) the FEC type and its strength (which affect the PER). While this should provide an intuitive explanation on the cross-layer operation as far as the physical layer functionalities are concerned, in the the next sections we introduce a rigorous mathematical framework to capture the FEC/modulation interactions.

E. MAC and Routing Interactions

The MAC functionality is based on a novel *hybrid medium access scheme* that combines Direct Sequence Code Division Multiple Access (DS-CDMA) for the data payload and a simple yet effective ALOHA access for a control header, which is transmitted *back-to-back* immediately before the data packet to help the next hop set its receiver, as explained in Sect. II-F. The MAC functionality incorporates a closed-loop distributed algorithm that interacts with the physical-layer functionality (described in Sect. II-C) to set the *optimal transmit power* and *code length*. The objective is to let signals arrive at the receiver with approximately the same mean power, thus minimizing the *near-far effect*[8], which affects the overall performance of CDMA systems [19], [20].

DS-CDMA compensates for the effect of multipath, which may heavily affect underwater acoustic channels especially in shallow water (i.e., when the depth is up to 100 m), by exploiting the time diversity in the underwater channel. This leads to high channel reuse and low number of packet retransmissions, which result in decreased battery consumption and increased network throughput. In such a scheme, however, the major problem encountered is the Multiuser Access Interference (MAI), which is caused by simultaneous transmissions from different users. In fact, the system efficiency is limited by the amount of total interference and not by the background noise exclusively [21]. Our MAC functionality, in conjunction with other functionalities such as FEC and modulation, aims at achieving three objectives, i.e., guarantee i) high network throughput, ii) low channel access delay, and iii) low energy consumption. To do so, it uses locally generated *chaotic codes* to spread transmitted signals on the optimal band, i.e., $< f_0^*, B^* >$, which guarantees a flexible and granular bit rate, built-in secure protection against eavesdropping, transmitter-receiver self-synchronization, and good auto- and cross-correlation properties.

The distributed closed-loop MAC functionality aims at setting the optimal combination of transmit power and code length at the transmitter side by relying on local periodic broadcasts of MAI values from active nodes. Sender i needs to transmit on the shared medium a data packet to j, and let j receive enough power to correctly decode the signal without impairing ongoing communications from h to k and from t to n. Because the system efficiency is limited by the amount of total interference, it is crucial for i to optimize its transmission, in terms of both transmit power and code length, in order to limit the near-far problem. These requirements are compactly expressed by the following set of constraints,

$$\frac{\int NI_j(f) \cdot TL_{ij}(f) df}{w_{ij} \cdot \Omega(BER_{ij})} \leq P_{ij} \leq \min_{k \in \mathcal{K}_i} \left[(\hat{R}_k - NI_k) \cdot TL_{ik} \right]. \tag{6}$$

[8]The *near-far effect* occurs when the signal received by a receiver from a sender near the receiver is stronger than the signal received from another sender located further. In this case, the remote sender will be dominated by the close sender.

In (6), $NI_j(f)$ [W/Hz] is the *noise plus MAI p.s.d.* at receiver j, while NI_k [W] is the *noise plus MAI power* at nodes $k \in \mathcal{K}_i$, with $\mathcal{K}_i$ being the set of nodes whose ongoing communications may be affected by node i's transmit power. In addition, w_{ij} and $w_{t_k k}$ are the bandwidth spreading factors of the ongoing transmissions from i to j and from t_k to k, respectively, where t_k is the node from which k is receiving data. The normalized received spread signal, i.e., the signal power after despreading, is $\hat{R}_k = R_k \cdot w_{t_k k} \cdot \Omega(BER_{t_k k})$; where R_k [W] is the user signal power that receiver k is decoding and $\Omega()$ is the MAI threshold, which depends on the target bit error rate. Finally, in (6), P_{ij} [W] represents the power transmitted by i to j, and $TL_{ij}(f)$ and TL_{ik} are the transmission losses from i to j and from i to $k \in \mathcal{K}_i$, respectively, i.e., $TL_{ij}(f) = TL(d_{ij}, f)$ and $TL_{ik} = TL(d_{ik}, f_{0ik})$, as in (1).

The left constraint in (6) imposes that the SINR^{-1} at receiver j be below a certain threshold, i.e., the power P_{ij} transmitted by i needs to be sufficiently high to allow receiver j to successfully decode the signal, given its current noise and MAI p.s.d. $NI_j(f)$. The right set of constraints in (6) imposes that the SINR^{-1} at receivers $k \in \mathcal{K}_i$ be below a threshold, i.e., the power P_{ij} transmitted by i must not impair ongoing communications toward nodes $k \in \mathcal{K}_i$. Consequently, to set its transmit power P_{ij} and spreading factor w_{ij}[9], node i needs to leverage information on the MAI and normalized receiving spread signal of neighboring nodes. This information is broadcast periodically by active nodes. In particular, to limit such broadcasts, a generic node k transmits only significant values of NI_k and $\hat{R}_k$, i.e., out of predefined tolerance ranges. Constraints (6) are incorporated in the cross-layer link optimization problem $\mathbf{P^{cross}_{layer}(i,j)}$ in (16).

In our cross-layer solution, the level of interference at potential receivers, i.e., their MAI, is used not only by the MAC functionality, but also by the routing functionality to decide for the best next hop. While a routing functionality implemented in isolation would find the best path from the sender to the destination only considering routing-layer metrics, our cross-layer routing/MAC solution finds the best path also considering the interference levels at the neighboring nodes (potential next hops): *a longer path characterized by a higher number of hops (i.e., a path that would likely be suboptimal according to only routing-layer information) may be chosen by our cross-layer solution as the optimal one if the direct path (i.e., the one that would guarantee the minimum number of hops) were composed of nodes characterized by high levels of MAI.* A reliable communication between these nodes, in fact, would require longer codes and/or higher transmit power. Also, given the fact that the bandwidth of underwater acoustic channels increases when the range decreases (i.e., shorter links provide higher bandwidth, which, in turns, leads to higher data rates, as discussed in Sect. II-C), our distributed cross-layer solution captures this property by composing paths using short links to exploit their higher bandwidth, thus achieving better end-to-end performance (Sect. III).

[9]We assume the spreading factor to be proportional to the chaotic code length, i.e., $w_{ij} = \alpha \cdot c_{ij}$. By proposing *chaotic codes* as opposed to *pseudo-random sequences*, a much higher granularity in the code length can be achieved as code lengths do not need to be a power of 2.

The proposed routing functionality relies on a geographical paradigm, which is very promising underwater for its scalability feature and limited required signaling, as shown in [3].

According to our distributed routing algorithm, a source or relay node i will select j^* as best next hop if

$$j^* = \begin{cases} \arg \min\limits_{j \in \mathcal{S}_i \cap \mathcal{P}_i^N} E_i^{(j)*} & \text{(Objective 1)} \\ \qquad OR & \\ \arg \max\limits_{j \in \mathcal{S}_i \cap \mathcal{P}_i^N} R_i^{(j)*} & \text{(Objective 2),} \end{cases} \tag{7}$$

where $E_i^{(j)*}$ [J/bit] (Objective 1) represents the minimum energy required to successfully transmit a payload bit from node i to the sink; and $R_i^{(j)*}$ [bps] (Objective 2) represents the maximum net bit rate that can be achieved from node i considering every outbound links in the path towards the sink. In (7), $\mathcal{S}_i$ is the *neighbor set* of node i and $\mathcal{P}_i^N$ is the *positive advance set*, which is composed of nodes closer to sink N than node i, i.e., $j \in \mathcal{P}_i^N$ iff $d_{jN} < d_{iN}$. The link metrics $E_i^{(j)*}$ and $R_i^{(j)*}$ in (7) are, respectively, the objective functions (8) and (9) of the cross-layer link optimization problem $\mathbf{P^{cross}_{layer}(i,j)}$. These metrics take into account the number of packet transmissions $\hat{N}^T_{ij^*}$ associated with the optimal link (i, j^*), given the optimal combination of modulation ($M^*_{ij} \in \mathcal{M}$) and FEC ($F^*_{ij} \in \mathcal{F}, {L^F_{P_{ij}}}^*$) techniques, and transmitted p.s.d. $S^*_{ij^*}(f) = K^*_{ij^*} - \tilde{NI}_{j^*}(f) \cdot TL_{ij^*}(f)$, $f \in < f^*_{0ij^*}, B^*_{ij^*} >$. Moreover, they account for the estimated hop-path length $\hat{N}^{Hop}_{ij^*}$ from node i to the sink given j^*.

The proposed optimization problem is a distributed communication solution for different multimedia traffic classes that optimizes the transmission considering every feasible outbound link from i, i.e., (i, j), $j \in \mathcal{S}_i \cap \mathcal{P}_i^N$, by choosing the optimal p.s.d. of the transmitted signal as well as band (K^*, f_0^*, B^*), modulation (M^*), FEC $(F^*, L_P^{F^*})$, and code length (c^*). The objective is set depending on the high-level application requirements. We consider two alternate application-dependent objectives, i.e., *Objective 1: minimize the average energy per bit successfully received at the destination*; and *Objective 2: maximize the average link net bit rate*, defined as the link bit rate R^b discounted by the number of transmissions N^T. While the first objective is expected to lead to a long network lifetime, the second aims at achieving a high end-to-end throughput. In the following, we cast the cross-layer link optimization problem.

$\mathbf{P^{cross}_{layer}(i,j)}$: **Cross-layer Link Optimization Problem**

Given (offline): E^b_{elec}, L^H_P, L^*_P, $\Phi^M()$, $\Psi^F()$, $PER^{e2e,(m)}_{max}$

Computed (online): d_{ij}, d_{iN}, NI_j, NI_k, $\tilde{d_{ij}}$, $\overline{q_{ij}}$, $\Delta D_i^{(m)}$, $\hat{Q}_{ij}$

Find: K^*_{ij}, f^*_{0ij}, B^*_{ij}, M^*_{ij}, F^*_{ij}, ${L^F_{P_{ij}}}^*$, c^*_{ij}

$$\underline{\textbf{Objective 1}}: \ \textbf{Minimize} \ \mathbf{E_i^{(j)} = E^b_{ij} \cdot \Pi^{e2e}_{ij}} \tag{8}$$

$$\textbf{OR} \ \underline{\textbf{Objective 2}}: \ \textbf{Maximize} \ \mathbf{R_i^{(j)} = R^b_{ij} \cdot {\Pi^{e2e}_{ij}}^{-1}} \tag{9}$$

Subject to:

(class-independent relationships)

$$R^b_{ij} = \frac{\eta(M_{ij}) \cdot B_{ij}}{c_{ij}}, \quad E^b_{ij} = 2E^b_{elec} + \frac{P_{ij}}{R^b_{ij}} \tag{10}$$

$$\Pi^{e2e}_{ij} = \frac{L^*_P}{L^*_P - L^H_P - L^F_{P_{ij}}} \cdot \hat{N}^T_{ij} \cdot \hat{N}^{Hop}_{ij} \tag{11}$$

$$SINR_{ij} = K_{ij} \frac{\int_{<f_{0ij},B_{ij}>} TL_{ij}(f)^{-1} df}{\int_{<f_{0ij},B_{ij}>} NI_j(f) df} - 1 \tag{12}$$

$$BER_{ij} = \Phi^{M_{ij}}\left(SINR_{ij}\right) \tag{13}$$

$$PER_{ij} = \Psi^{F_{ij}}\left(L_P^*, L_{Pij}^F, BER_{ij}\right) \tag{14}$$

$$\hat{N}_{ij}^{Hop} = \max\left(\frac{d_{iN}}{<d_{ij}>_{iN}}, 1\right) \tag{15}$$

(class-independent set of constraints)

$$P_{ij}^{min}(c_{ij}, BER_{ij}) \le P_{ij} \le \min[P_{ij}^{max}, P_i^{max}] \tag{16}$$

where,

$$P_{ij} = K_{ij} \cdot B_{ij} - \int_{<f_{0ij},B_{ij}>} NI_j(f) \cdot TL_{ij}(f) df \tag{17}$$

$$P_{ij}^{min}(c_{ij}, BER_{ij}) = \frac{\int_{<f_{0ij},B_{ij}>} NI_j(f) \cdot TL_{ij}(f) df}{\alpha \cdot c_{ij} \cdot \Omega(BER_{ij})} \tag{18}$$

$$P_{ij}^{max} = \min_{k \in \mathcal{K}_i} \left[(\hat{R}_k - NI_k) \cdot TL_{ik}\right]. \tag{19}$$

Notations of *class-independent relationships and constraints*:

- $L_P^* = L_P^H + L_{P\,ij}^F + L_{P\,ij}^N$ [bit] is the *fixed* optimal packet size, solution of an *offline* optimization problem presented in [3], where L_P^H is the header size of a packet, while $L_{P\,ij}^F$ is the *variable* FEC redundancy of each packet from i to j.
- $E_{elec}^b = E_{elec}^{trans} = E_{elec}^{rec}$ [J/bit] is the *distance-independent* energy to transit one bit, where E_{elec}^{trans} is the energy per bit needed by transmitter electronics (PLLs, VCOs, bias currents) and digital processing, and E_{elec}^{rec} represents the energy per bit utilized by receiver electronics. Note that E_{elec}^{trans} does not represent the overall energy to transmit a bit, but only the distance-independent portion of it.
- $E_{ij}^b = 2E_{elec}^b + P_{ij}/R_{ij}^b$ [J/bit] in (10) is the energy to transmit one bit from i to j, when the transmitted power and the bit rate are P_{ij} [W] and R_{ij}^b [bps], respectively. The second term, P_{ij}/R_{ij}^b, is the *distance-dependent* portion of the energy to transmit a bit.
- P_i^{max} [W] is the maximum transmitting power for node i.
- $BER = \Phi^M(SINR)$ represents the bit error rate, given the SINR and the modulation scheme $M \in \mathcal{M}$, while $\eta(M)$ is the spectrum efficiency of modulation M.
- $PER = \psi^F(L_P, L_P^F, BER)$ represents the link packet error rate, given the packet size L_P, the FEC redundancy L_P^F, and the bit error rate (BER), and it depends on the adopted FEC technique $F \in \mathcal{F}$.
- TL_{ij} is the transmission loss (in absolute values) from i to j, which is computed according to the Urick model in (1).
- $\hat{N}_{ij}^T$ is the number of transmissions of a packet sent by i. The relation $N_{ij}^T = (1 - PER_{ij})^{-1}$, which approximates the average number of transmissions such that the packet be correctly decoded at j, assumes independent errors among consecutive packets; this assumption holds when the *channel coherence time* is shorter than the *retransmission timeout*, i.e., the time before retransmitting an unacknowledged packet, which is the case in UW-ASNs.
- $\hat{N}_{ij}^{Hop} = \max\left(\frac{d_{iN}}{<d_{ij}>_{iN}}, 1\right)$ is the estimated number of hops from node i to the surface station (sink) N when j is selected as next hop, assuming that the following hops will guarantee the same advance towards the surface station. This estimate has three nice properties: 1) it does not incur any signaling overhead as it is locally computed and does not require end-to-end information exchange, 2) its accuracy increases as the density increases, and 3) as the distance between the surface station and the current node decreases.
- $<d_{ij}>_{iN}$, which we refer to as *advance*, is the projection of d_{ij} onto the line connecting node i with the sink.

As described in Sect. II-B, we envision that underwater multimedia sensor networks will need to provide support and differentiated service to applications with different QoS requirements, ranging from delay sensitive to delay tolerant, and from loss sensitive to loss tolerant. Hence, in this work we consider the following four traffic classes: **Class I** (delay-tolerant, loss-tolerant), **Class II** (delay-tolerant, loss-sensitive), **Class III** (delay-sensitive, loss-tolerant), and **Class IV** (delay-sensitive, loss-sensitive). While for loss-sensitive applications a packet is locally retransmitted until it is correctly decoded at the receiver (or if the maximum number of retransmissions is reached), for loss-tolerant applications packets are transmitted only once on each link and are protected unequally, depending on the importance of the data they are carrying for correct reconstruction.

(additional class-dependent constraints)

$$\textbf{Class I} = \begin{cases} \hat{N}_{ij}^T = 1 \\ 1 - \left(1 - PER_{ij}\right)^{\hat{N}_{ij}^{Hop}} \le PER_{max}^{e2e,(m)} \end{cases}$$

$$\textbf{Class II} = \left\{ \ \hat{N}_{ij}^T = (1 - PER_{ij})^{-1} \right.$$

$$\textbf{Class III} = \begin{cases} \hat{N}_{ij}^T = 1 \\ 1 - \left(1 - PER_{ij}\right)^{\hat{N}_{ij}^{Hop}} \le PER_{max}^{e2e,(m)} \\ \frac{\tilde{d_{ij}}}{q_{ij}} + \delta(\gamma) \cdot \sigma_{ij}^q \le \left(\frac{\Delta D_i^{(m)}}{\hat{N}_{ij}^{Hop}}\right) - \hat{Q}_{ij} - \frac{L_P^*}{R_{ij}^b} \end{cases}$$

$$\textbf{Class IV} = \begin{cases} \hat{N}_{ij}^T = (1 - PER_{ij})^{-1} \\ \frac{\tilde{d_{ij}}}{q_{ij}} + \delta(\gamma) \cdot \sigma_{ij}^q \le \left(\frac{\Delta D_i^{(m)}}{\hat{N}_{ij}^{Hop}}\right) - \hat{Q}_{ij} - \frac{L_P^*}{R_{ij}^b}. \end{cases}$$

Notations of additional *class-dependent constraints*:

- $PER_{max}^{e2e,(m)}$ is the maximum end-to-end error rate for packet m.
- $\Delta D_i^{(m)} = D_{max} - \left(t_{i,now}^{(m)} - t_0^{(m)}\right)$ [s] is the time-to-live of packet m arriving at node i, where D_{max} [s] is the maximum end-to-end delay, $t_{i,now}^{(m)}$ is the arriving time of m at i, and $t_0^{(m)}$ is the time m was generated, which is time-stamped in the packet header by its source.
- $T_{ij} = L_P^*/R_{ij}^b + T_{ij}^q$ [s] accounts for the packet transmission delay and the propagation delay associated with link (i, j); to derive the last constraint for Classes III and IV, we consider a Gaussian distribution for T_{ij}, i.e., $T_{ij} \backsim \mathcal{N}(L_P^*/R_{ij}^b + \overline{T_{ij}^q}, {\sigma_{ij}^q}^2)$; for the mathematical derivation of the constraint, due to lack of space we refer the interested reader to [3].
- $\hat{Q}_{ij}$ [s] is the network queueing delay estimated by node i when j is selected as next hop, computed according to the information carried by incoming packets and broadcast by neighboring nodes.

Note that sender i optimally decouples the routing decision, which is based on (7), from the solution of $\mathbf{P_{layer}^{cross}(i, j)}$, whose output is the optimal metric $E_i^{(j)*}$ (or $R_i^{(j)*}$), input of the routing decision itself. Therefore, sender i can optimally decouple the cross-layer algorithm into two *sub-problems* (to be solved sequentially):

1) Minimize the link metric $E_i^{(j)}$ (or maximize $R_i^{(j)}$) for each of its feasible next-hop neighbors (Algorithm 1 presents a possible space-search approach) *(physical functionalities)*;
2) Pick as best next hop that node j^* associated with the best link metric *(MAC/ Routing functionalities)*.

This means that the generic node i does not have to solve a complicated optimization problem to find its best route towards a sink. Rather, it only needs to sequentially solve the two aforementioned sub-problems *with no loss of optimality*. The first sub-problem has a complexity $O(|\mathcal{S}_{th}| \cdot |\mathcal{M}| \cdot |\mathcal{F}|)$, where $|\mathcal{S}_{th}|$, $|\mathcal{M}|$, and $|\mathcal{F}|$ are the number of different SNR_{th} thresholds, modulation techniques, and FEC schemes, respectively, used in combination with Algorithm 2. The second sub-problem has a complexity $O(|\mathcal{S}_i \cap \mathcal{P}_i^N|)$, i.e., proportional to the number of the sender's neighboring nodes with positive advance towards the sink. Moreover, this operation does not need to be performed every time a sensor has to route a packet, but only when the channel or the traffic conditions, i.e., the structure of the MAI in the neighborhood, have changed. While this cross-layer approach - which is the solution of a local optimal problem - does not guarantee *global optimality* as a sender does not have global knowledge of the network, it achieves the 'best' possible performance given the limited information at the sender.

Algorithm 1 Cross-layer Link Optimization (given i, j, d_{ij})

$E_{min} = \infty$ [or $R_{max} = 0$] {initialization}
for th=1 : $|\mathcal{S}_{th}|$ **do**
  for mo=1 : $|\mathcal{M}|$ **do**
    for fe=1 : $|\mathcal{F}|$ **do**
      $(SNR, K, f_0, B) \leftarrow$ **Algorithm 2(**d_{ij}**,** $SNR_{th} = th$**)**
      $PER = \psi^{fe}\big(L_P, L_P^F(fe), \Phi^{mo}(SINR)\big)$
      Solve $\mathbf{P}^{\mathbf{cross}}_{\mathbf{layer}}$, Calculate $E_i^{(j)}$ (8) [OR $R_i^{(j)}$ (9)]
      if ($E_i^{(j)} < E_{min}$**) [OR** $R_i^{(j)} > R_{max}$**] then**
        $E_{min} = E_i^{(j)}$ **[OR** $R_{max} = R_i^{(j)}$**]**
        $(fe, mo, K, f_0, B)^* = (fe, mo, K, f_0, B)$
      end if
    end for {end FEC cycle}
  end for {end modulation cycle}
end for {end SNR cycle}

Algorithm 2 Link Transmission (given d and SNR_{th})

$f_0 =\text{argmin}_f[N(f) \cdot TL(d, f)]$ {optimal f_0}
$K^{(0)} = [\min_f N(f)] \cdot TL(d, f_0)$ {initialization}
$stop = 0,\ n = 0$
while ($stop == 0$) **do**
  $n = n + 1$, Find $B^{(n)}$ $s.t.$ $K^{(n-1)} \geq N(f) \cdot TL(d, f)$
  Calculate $SNR^{(n)}$ from (4) using $K^{(n-1)}$ and $B^{(n)}$
  if ($SNR^{(n)} \geq SNR_{th}$) **then**
    $stop = 1$
  else
    $K^{(n+1)} = (1 + \epsilon) \cdot K^{(n)}$ $\{\epsilon \in \mathbb{R}^+\}$
  end if
end while

F. Protocol Operation

Algorithm 1 makes use of the solution of Algorithm 2, which provides four communication parameters, the three defining the transmit signal (i.e., K, f_0, and B), and the associated estimated SNR at the receiver. Algorithm 1 will use these parameters to find the best FEC/modulation combination. While some iterations between the two algorithms are needed as they cannot be entirely decoupled, using this approach the complexity is reduced while still leading to the optimal solution of the cross-layer optimization problem.

Once this optimization problem has been solved at sender i, and the *optimal communication parameters* (i.e., K^*, f_0^*, B^*, M^*, F^*, $L_P^{F^*}$, c^*) have been found, i randomly accesses the channel by transmitting a short header called *Extended Header (EH)*. The EH is sent using a *common chaotic code* c_{EH} known by all devices. Sender i transmits to its next hop j^* the short header EH. The EH contains information about the final destination, i.e., the surface station, the chosen next hop j^*, and the parameters that i will use to generate the *chaotic spreading code* of length c^* for the actual data packet that j^* will receive from i. Immediately after the transmission of the EH, i transmits the data packet on the channel using the *optimal communication parameters* set by the cross-layer algorithm.

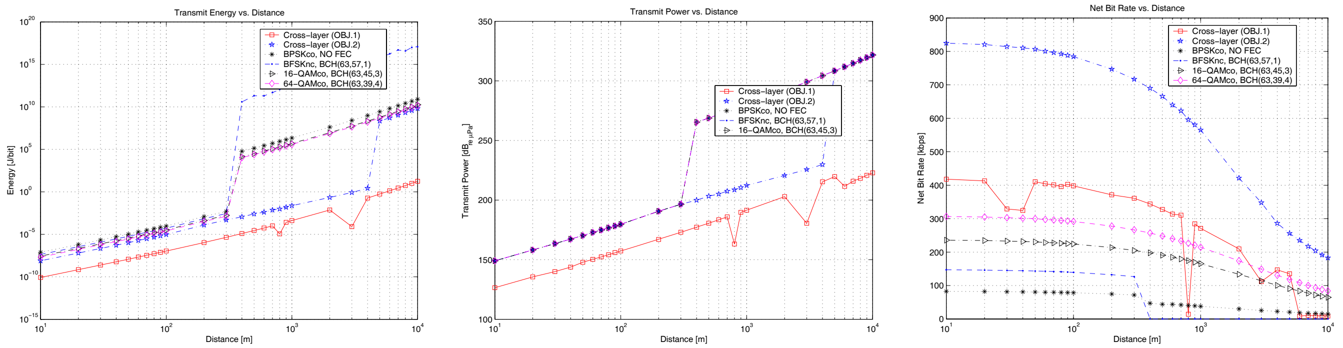
Note that the protocol does not have to send control packets before the actual data packet is transmitted. This is because the packet - composed of the extra header EH and the actual data packet (payload plus standard header) - uses a hybrid MAC to access the channel, i.e., it simultaneously accesses the channel using ALOHA-like MAC (for the extra header EH) and locally adapting its power and code length as in standard distributed CDMA MAC schemes (for the data packet). *This novel approach is motivated by the need to achieve high channel utilization efficiencies* to compensate for the low-bandwidth shared medium and the huge propagation delay affecting the underwater environment (five orders of magnitude larger than in terrestrial wireless networks).

If no collision occurs during the reception of the EH, i.e., if i is the only node transmitting an EH in the neighborhood of node j^*, j^* will be able to synchronize to the signal from i, despread the EH using the common code, and acquire the carried information. Then, if the EH is successfully decoded, receiver j^* will be able to locally generate the chaotic code that i used to send its data packet, and set its decoder according to the optimal communication parameters used by i in such a way as to decode the data packet. Once j^* has correctly received the packet from i, it acknowledges it by sending an ACK packet to j using code c_A. In case i does not receive the ACK before a timeout T_{out} expires, for delay-tolerant and loss-sensitive traffic classes it will keep transmitting the packet until a maximum transmission number is reached. If sender i does not have updated information about the MAI in j^*, it increases the code length every time a timeout expires to improve the probability that the packet be decoded.

III. Performance Evaluation

We compare here the performance achieved by our-cross layer solution against that achieved by individual communication functionalities that do not share information and operate in isolation (traditional layered approach). We compare results obtained when the objective function of our cross-layer optimization problem is either Objective 1 (energy minimization) or 2 (throughput maximization).

As far as the interactions between physical layer functionalities are concerned, Fig 3 show the energy per bit $E_i^{(j)}$ [J/bit], transmit power P [$\text{dB}_{\text{re}\,\mu\text{Pa}}$], and net bit rate $R_i^{(j)}$ [kbps] versus distance d [m] for the proposed cross-layer solution when both Objective 1 (OBJ.1) and 2



(a) (b) (c)

Fig. 3. Energy per bit $E_i^{(j)}$ [J/bit] (a), transmit power P $[\mathrm{dB_{re\,\mu Pa}}]$ (b), and net bit rate $R_i^{(j)}$ [kbps] (c) vs. distance d [m] for the proposed cross-layer solution (Objectives 1 and 2) and for four fixed FEC/modulation combinations.

(OBJ.2) are considered. The comparison is made against the four best fixed FEC/ modulation combinations: i) coherent BPSK/NO FEC, ii) non-coherent BFSK/BCH(63,57,1), iii) coherent 16-QAM/BCH(63,45,3), and iv) coherent 16-QAM/BCH(63,39,4).

As can be seen, our solution outperforms competing fixed schemes when either objective is selected in terms of both energy and throughput. In particular, in Figs. 3(a) and 3(b), the curves associated with OBJ.1, representing the transmit energy and power, respectively, for a payload bit to be successfully decoded at the receiver, are always above any other curve associate with a fixed FEC/ modulation combination. Moreover, the performance gain of our cross-layer solution over the best FEC/ modulation combination out of the four considered increases as the distance increases. The same conclusion can be drawn looking at Fig. 3(c), which reports the net bit rate vs. distance for our solution as well as for the best four competing fixed schemes. Again, the curve depicting the performance of our solution when OBJ.2 is set as objective function of the optimization problem outperforms any of the other four curves whichever distance is considered.

As far as the interactions between MAC and Routing functionalities are concerned, Fig. 4 report the average normalized used energy, the normalized successfully received packets, and the average packet delay versus number of sensors. We considered a variable number of sensors (from 10 to 50) randomly deployed in a 3D volume of 500x500x500 m^3. Performance results refer to the three cases of OBJ.1 and OBJ.2 for our cross-layer solution, and the case where a CDMA-based MAC [4] and geographically-based routing [3] run individually. In Figs. 4(a-b) our cross-layer solution using OBJ.1 outperforms the MAC+Routing case (for Class II); in Fig. 4(c) this is again the case when OBJ.2 is used (for Class III). These positive results are due to the fact that our solution jointly optimizes the considered communication functionalities, thus exploiting synergies that lead to improved end-to-end system performance.

Results show that by minimizing at each node the energy to deliver packets (i.e., OBJ.1), in the cases in which the network density is not too inhomogeneous, the network topology has not very different node degrees, and the traffic patter is not highly asymmetric, longer network lifetimes are experienced when our cross-layer solution is used. Specifically, the lifetime gain is in the $20-30\%$ range depending on the number of nodes, being higher for larger networks (number of nodes around 50) in which there is greater flexibility on available end-to-end paths. In the other (less common) cases, the maximization of the network lifetime should be achieved not only through ‘energy minimization’, but also through ‘load balancing’. This is due to the fact that in such cases some nodes may be “essential” for the network to keep being connected. Hence, a networking strategy that would only try to save energy may possibly lead to the energy depletion of such nodes, which in turn could result in a shorter network lifetime.

IV. Conclusions and Future Work

We explored the interaction of key underwater communication functionalities and developed a cross-layer communication solution that allows for the efficient utilization of the bandwidth-limited high-delay underwater acoustic channel. We showed that end-to-end network performance improves in terms of both energy and throughput when highly specialized communication functionalities are integrated in a cross-layer module. As future work, we will develop ad-hoc scheduling mechanisms to simultaneously handle traffic classes with different QoS requirements and we will incorporate end-to-end rate control functionalities to provide fair congestion avoidance in dynamic conditions.

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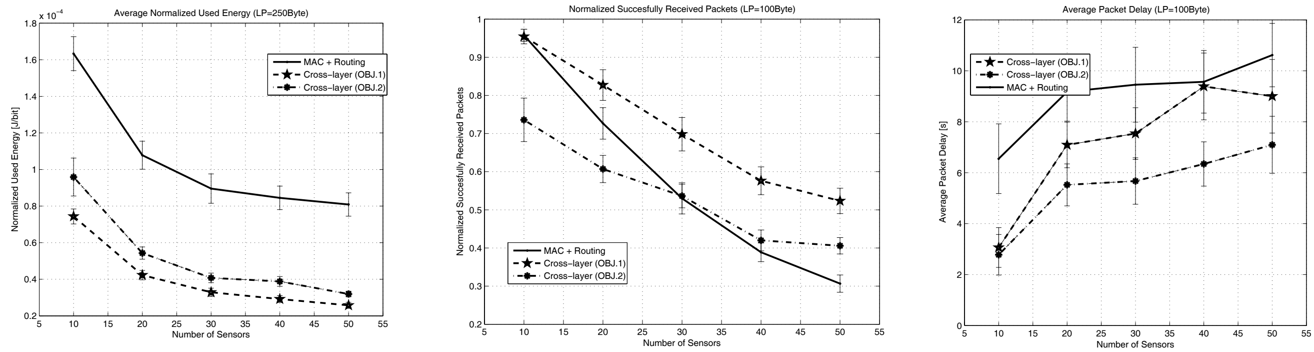

(a) (b) (c)

Fig. 4. (a): Average normalized energy vs. no. of sensors for Class II (delay-tolerant, loss-sensitive); (b): Normalized successfully received packets vs. no of sensors for Class II (delay-tolerant, loss-sensitive); (c): Average packet delay vs. no. of sensors for Class III (delay-sensitive, loss-tolerant).

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