Virtual Unequal Error Protection in Underwater Image Transmission

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***Abstract*—Due to its applications in marine research, oceanographic, and undersea exploration, underwater communication has been recently under intense investigation. In the last years, several works have studied the communication between autonomous underwater vehicles (AUV). Although underwater communication has been improving its performance (in terms of bandwith, QoS, etc.), image transmission in AUVs networks is still considered a frontier work. Here, we address progressive image transmission for AUVs fleet. By taking into consideration the tight constraints imposed by the underwater channel, we propose a method able to improve the performance by exploiting the feature of the progressive images. Several scenarios have been investigated to demonstrate the benefit of the proposed model, focusing on the tradeoff between QoS vs. delays and energy consumption.**

***Index Terms*—underwater communications, image transmission, underwater acoustic networks.**

I. Introduction

In the last decades, due to the increasing attention to undersea applications (e.g., oceanographic researches, exploration, offshore oil industry, etc.), underwater communications have been deeply investigated. Since the terrestrial radio links are substantially different from their underwater counterparts, technology and communication models for the former might not be suitable for the marine scenario [1]. Indeed, underwater communication technologies are mainly based on acoustic signal transmission, which present numerous issues too specific to be addressed by means of standard terrestrial techniques.

Recently, several improvements have been achieved in the autonomous underwater vehicle (AUV) technology turning the idea of employing multiple AUVs on a coordinated mission into a realistic goal. In a hypothetical application aimed at monitoring undersea environments, for example, a fleet of AUVs might cover an area wide far beyond the possibilities of a single vehicle and guarantying at the same time a better communication with the surface, taking benefit of multi-hop communication in a decentralized network in which there is no a priori established infrastructure, and the nodes alone are responsible for multi-hop message relaying. In a AUVs fleet scenario, each vehicle is a candidate for relaying packets, leading to a flexible network. Since nodes position and number can considerably affect the overall performance, according to the application and constraints considered, an optimization of the network density and topology is required [2]. Given that the path loss strictly depends on both the central frequency and the link distance [1], by increasing the number of nodes employed in the communication, the link distance is reduced, leading to a more reliable communication. On the other hand, the higher the number of nodes, the greater the transmission delay and the network complexity. The optimal tradeoff between reliability and energy consumption/network delay was investigated in [3], where the authors, following a top-down approach, analyzed design challenges of each layer in the network protocol stack for underwater sensor networks.

Even if in many applications the interest in multimedia transmissions has been constantly growing, underwater communications in this field have always been and still remain challenging due to low throughput, high path loss, and multipath degradation in underwater channels. While sonar images can be sufficient for application aimed at detecting animals and their movement [4], they suffer from major shortcomings when other oceanographic scopes are considered. In monitoring the animal behavior, for example, good-quality digital images or video are required. The need of digital image transmission over hostile environments, such as the underwater one, can be met by the progressive image/video source coding. This coding technique allows to reconstruct the source progressively from the prefix of the received bits, and allows partial decoding at various resolutions from a single compressed bitstream. Due to this features, progressive images provide high granularity and scalability to the user, suitable for limited bandwidth channels. As a drawback, since an error in the bitstream renders the subsequent bits useless, the encoded source is extremely sensible to channel impairments. To offer reliable progressive transmission, an unequal error protection (UEP) can be adopted at the physical layer, increasing the modem complexity [5]–[9], or it can be managed by the routing protocol. In this work, we propose a cross-layer adaptive routing method aimed at enhancing the quality of progressive images transmissions in underwater communication. In particular, we propose a virtual UEP able to adapt the number of possible retransmission adapting the number of retransmission allowed by the algorithm to the relative importance of the information bits to transmit. After providing basic notions on both the progressive source coding and the adopted routing algorithm, we describe our method, showing the improvement that can be achieved compared to a system with no consideration of the priority of the bits. In particular, we demonstrate that the more critical the system (e.g., the higher the network density,

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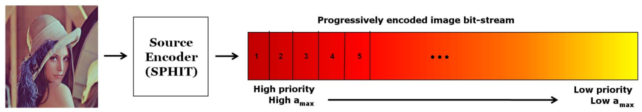


Figure 1. Progressive source coding.

or the nodes mobility) the higher is the gain achieved by the virtual UEP method when compared to the classic one [virtual equal error protection (EEP) method].

This paper is organized as follows: in Section II, we provide an overview of the source coding, and of the routing algorithm adopted in this work. In Section III, the cross-layer routing method proposed in this paper, together with the problem formulation is provided. Section IV describes the considered scenario, and provides a simulation setup. In Section V, simulation results and discussion are shown. Finally, Section VI gives summary and conclusions.

II. Preliminars

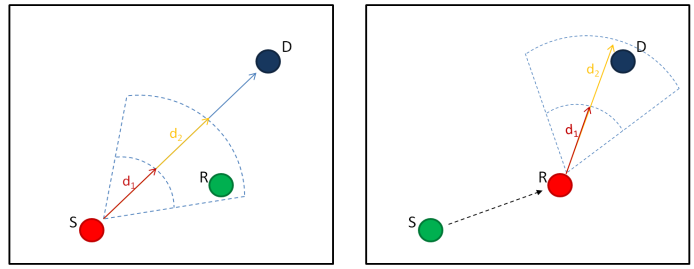
In the following, we provide a brief description of the progressive image source coding, and a general overview on the underwater routing algorithm adopted in this work.

A. Progressive Images

Progressive images have many attractive features [10]. First, the quality of the decoded image is proportional to the received data rate, it means that the more bits are available for the decoding, the higher is the quality of the reconstructed image. Second, the decoding process can be stopped as soon as a target bit rate or a target distortion metric is met, and the quality will be the best possible for that bit rate. Third, as a consequence of the previous properties, one bitstream can be truncated at different data rates, providing several qualities. Thus, progressive image technique is a suitable approach for heterogeneous networks (e.g., networks with different QoS, or available bandwidth). As a drawback, since an error generally renders the subsequent bit useless, the transmission quality is highly sensible to channel impairments. In Fig. 1, the bits priority of a progressive encoded bitstream is highlighted. Since each bit is more important than the next one, the communication protocols should take into account this order of priority of the encoded bitstream.

B. Routing Algorithm

As already mentioned, the introduction of possible relays in the network may deeply improve the system performance by reducing the distance between sender and receiver, leading to a more efficient communication. In this scenario, several works have been considered aimed at evaluating the optimal routing protocol to design ad-hoc networks [11], [12]. In [11] the authors evaluated a routing algorithm able to choose the best hop-distance with the final goal of minimizing the network energy consumption, for a quasi-static scenario. A dynamic scenario, more suitable for AUVs networks, has been investigated in [12], where routing methodology for both static



(a) Phase I: the source can not reach the destination and looks for an intermediate node.

(b) Phase II: after receiving the packet from the source, the relay node looks for other intermediate nodes or for the destination.

Figure 2. Focused beam routing protocol example. S, R, and D are respectively the source, relay, and destination nodes. The red color denotes busy nodes, the green the available ones, while the blue nodes are the destinations.

and mobile nodes is provided. Here, we adopt this latter method, the Focused Beam Routing (FBR) protocol. We refer the reader to [12] for details on the FBR method, hereafter we only provide a brief description.

Since in AUVs networks, each node can change its location, the FBR routing algorithm requires that each node is aware only of the location of its own and of its final destination. By sending multicast request-to-send (RTS) with the DACAP[1] protocol the sender will ask to all the nodes within a given range (depending on the power level used for the RTS) to be its relay. Each node within this area, if not already involved in any other communication, will reply with clear-to-send (CTS), sending its own ID and location. Among the possible candidates, the sender will select one as its relay.

A possible example of the FBR protocol is depicted in Fig. 2, and assumes that a packet needs to be transmitted from the node S to a destination node D, able to communicate to the surface. The peer S will start a RTS/CTS procedure for each packet. When the RTS is sent, if no neighbor nodes are available, S will retransmit the RTS with a higher power level. This first step is illustrated in Fig. 2(a), where the source does not reach any node with a first power level, able to cover a cone area with diameter d_1. Thus, a higher power level is considered for the RTS transmission, covering a wider area. In this case, an intermediate node (relay) is reached and considered for multi-hop transmission. After receiving the packet from S, the relay R will search for the destination or another relay node, Fig. 2(b). When neither the relay nor destination nodes are reached even with the highest power level, the source will start again the RTS/CTS procedure. After a maximum number of attempts ($a_{\max}$), if no CTS is received, the current packet

[1]The channel access protocol adopted for ad-hoc underwater acoustic networks is the Distance Aware Collision Avoidance Protocol (DACAP) [13]. This non-synchronized protocol allows a node to use different hand-shake lengths for different receivers to minimize the average handshake duration and to save transmission energy by avoiding collisions while maximizing throughput.

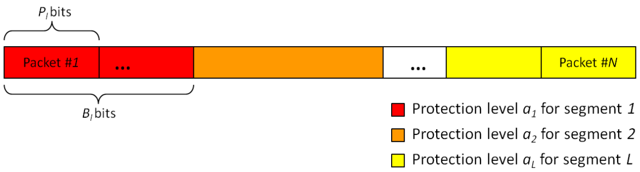


Figure 3. Virutal UEP method.

is discarded.

III. Problem Formulation

We now describe the proposed method, associated to the FBR routing algorithm. In the classical FBR, the number of maximum retransmission $a_{\max}$ is a fixed value. When progressive images transmission is considered, without optimizing this parameter, extremely low performance might be achieved. Assuming that N packets are transmitted for each image, if the first packet is not correctly received, the whole image reconstruction is compromised. To overcome this limitation, the parameter $a_{\max}$ should be increased. Note that the higher $a_{\max}$, the higher the probability of a correct reception of the packet, but the higher the network congestion. A degenerative case, with $a_{\max} \to \infty$ for all the packets, would guarantee the minimization of the reconstructed image distortion, at the cost of a substantial increasing of energy consumption and delay of the network. In this case, $a_{\max}$ could guarantee a sufficient protection for the first packets, overprotecting the last ones. On the contrary, a lower $a_{\max}$ value could give a sufficient protection to the last packets, making the first bits more sensible to the channel impairments and jeopardizing therefore the reception of the image. Then, for each transmitted packet, the parameter $a_{\max}$ should be optimized, taking advantage of the progressive nature of the bitstream: different $a_{\max}$ values shall be considered for each packet, depending on the importance of its payload. In particular, the higher the priority of the bits, the higher the $a_{\max}$ value.

Denoting by B_{tot} the bits to transmit for each image, we divide the encoded bitstream into L segments of B_l bits, where

$$L = \left\lceil \frac{B_{\text{tot}}}{B_l} \right\rceil \quad (1)$$

Due to the progressive nature of the bitstream, each j-th segment has its own priority level and thus its own maximum number of attempts a_j, as illustrated in Fig. 3. It means that $\mathbf{A} = [a_1, a_2, \ldots, a_L]$ is the vector that associates the protection level a_j to the j-th segment, where $a_j \geq a_{j+1}$. Based on the packet length P_l, the bunch of B_l bits can be transmitted in one or more packets. In particular, we evaluate the number of packets to transmit for each image as

$$N = \left\lceil \frac{B_l}{P_l} \right\rceil \cdot L$$

Our goal is to evaluate the best protection level able to minimize the expected distortion. Assuming that, when the first n packets are correctly received, $R_n = P_l \times n$ is the number of bits in input to the decoder, and $D(R_n)$ is the distortion of reconstructed image, the expected distortion associated to $\mathbf{A}$ is given by

$$\overline{D}_{\mathbf{A}} = \sum_{n=0}^{N} D(R_n) P_N(n) \quad (2)$$

where N is the total number of transmitted packets and $P_N(n)$ is the probability mass function (PMF) of correctly receiving the first n packets. For each system configuration (i.e., for a given density network, mobility, etc.), the best protection level $\mathbf{A}^\star$ is the vector such that

$$D_{\mathbf{A}^\star} = \min_{\mathbf{A}} \left\{ \overline{D}_{\mathbf{A}} \right\} \quad (3)$$

In the following, we analyze the behavior of the optimal UEP level as a function of the network congestion and channel conditions for both static and mobile nodes. We compare the proposed method to system with no protection at all or other levels of virtual protection. The results highlight the tradeoff between image quality vs. energy consumption and delay. We demonstrate that, the more critical is the transmission, the higher is the gain achieved by the UEP compared to other protection levels, justifying the possible increasing of delay or energy consumption.

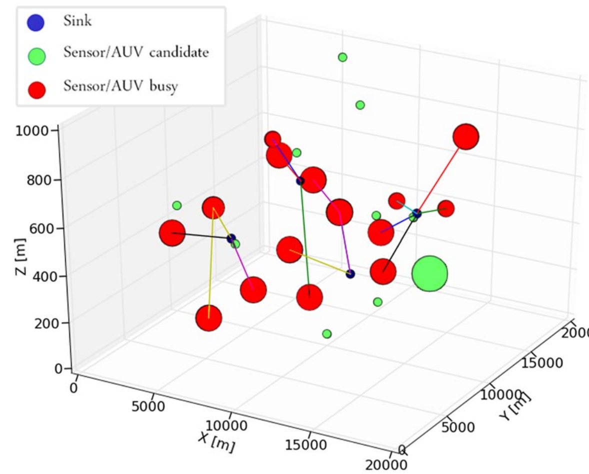


Figure 4. Simulated scenario.

IV. Simulation Setup

All the results were carried out with the python-based AUVNet simulator, described in [12]. The simulated scenario, depicted in Fig. 4, is characterized by an area of $400\ \text{km}^3$, with 4 sinks (i.e., fixed nodes able to communicate to the surface that are the destinations of the packets), and $16, 25$ or 49 fixed or mobile nodes, collocated in random positions within the area. We assume that a single image is transmitted in 3 segments (i.e., $L = 3$) each consisting of $B_l = 9600$ bits, and we consider four different protection levels:

- *NOP*, no protection;
- *First*, high protection for only the first portion of bits;

	a_1	a_2	a_3
NOP	1	1	1
First	6	1	1
EEP	2	2	2
UEP	6	4	1

Table I
PROTECTION VECTOR $\mathbf{A}$ FOR THE DIFFERENT SIMULATED SCENARIO.

- *EEP*, equal level of protection;
- *UEP*, unequal error protection level.

In Table I the protection level a_j is reported for each segment of each simulated scenario.

All the results are provided in terms of quality of the reconstructed image, received packet PMF, and tradeoff between quality vs. delay and collisions. The reconstructed image quality is in terms of peak signal-to-noise ratio (PSNR), that is evaluated as

$$\text{PSNR} = 10 \log_{10} \frac{255^2}{\overline{D}_{\mathbf{A}}} .$$

As already mentioned, the received packet PMF $P_N(n)$ is the probability of correctly receiving the first n packets among N. In the results section, rather than considering the distribution of the received packets, we provide the quality PMF, $P_Q(q)$. Denoting by q the reconstructed image quality when n packets are received, it follows that

$$P_Q(q) = \mathbb{P}\{\text{PSNR} = q\} = P_N(n) . \quad (4)$$

V. RESULTS

We now provide results for several network densities and for both static and mobile nodes.

Fig. 5 shows the PMF of the decoded quality for the scenario with 20 nodes and packet length $P_l = B_l$. When no protection is considered (*NOP* curve), the probability of achieving a quality level in the range $[14.5 - 33]$ dB is almost 0.1, while is almost 0.6 the probability of experiencing a PSNR of 34 dB. It follows that for networks with 20 nodes, there is a high probability of correctly receiving all the packets. By adopting a virtual protection, the system performance can be further improved. Considering the *First* curve, the probability of having a PSNR lower than 26 dB is negligible, while, for both *EEP* and *UEP*, the probability of achieving the best quality (34 dB) is almost one. For this density network, since the EEP level is able to achieve good performance, an *UEP* protection is not necessary. When the number of nodes within the network increases (Fig. 6), the need of protection increases accordingly. When no protection is considered, it is more likely to experience a PSNR of 14.5 dB rather than the maximum PSNR value. By adopting any protection level, the probability of receiving images with very low performance (PSNR$<$ 25 dB) is drastically reduced. Note that the *UEP* outperforms the other systems, even the one with *EEP* protection: when the *UEP* level is considered, the image

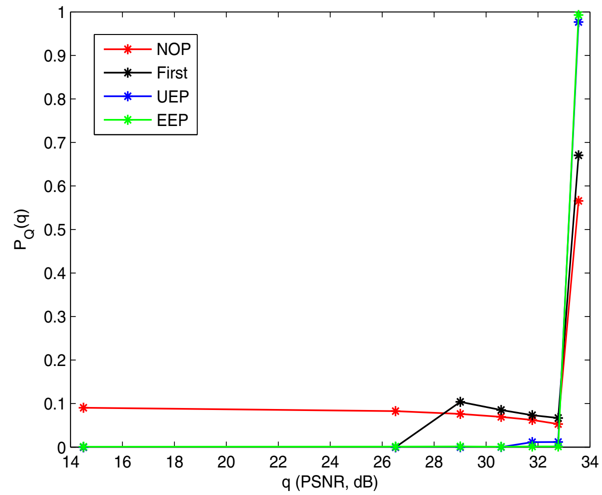


Figure 5. PSNR distribution for an area of 400 km^3, and 20 total nodes. The packet length P_l is equal to $B_l = 9600$ bits, and the number of packets to transmit is $N = 6$.

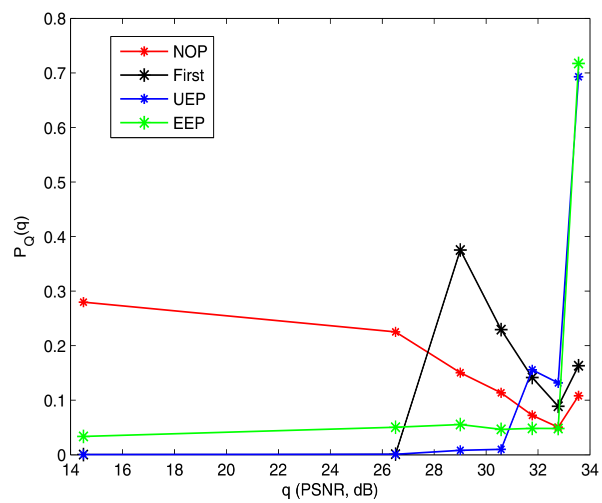


Figure 6. PSNR distribution for an area of 400 km^3, and 40 total nodes. The packet length P_l is equal to $B_l = 9600$ bits, and the number of packets to transmit is $N = 6$.

qualities that most likely are experienced by the system are higher than 32 dB.

The gain of *UEP* over the *NOP* technique can be observed even for different packet length. Fig. 7 and Fig. 8 shows the PSNR distribution for scenarios with 20 and 53 fixed nodes, respectively. We consider the packet length equal to $B_l, B_l/2, B_l/4$, and the number of packets to transmit $N = 3, 6, \text{and } 12$, respectively. For both the scenarios, a higher N achieves higher performance, and mostly important, the systems with UEP outperforms the ones with no protection. For example, for all the *NOP* curve in the scenario with 20 nodes (Fig. 7), the probability of achieving a quality level in the range $[14.5-33]$ dB is about $0.1-0.2$, while is almost 0.6

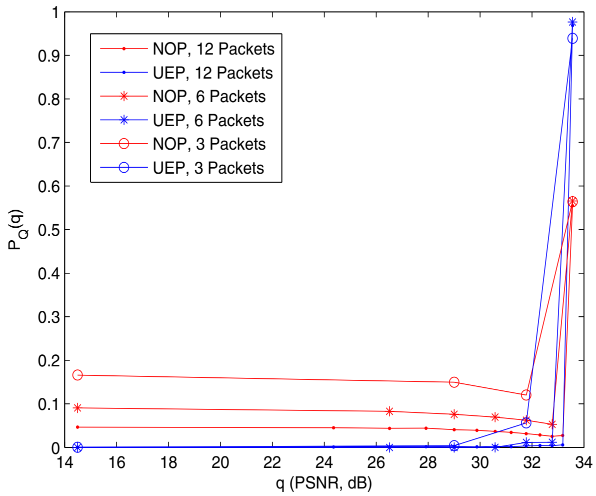


Figure 7. Quality PMF for systems with several packet length, with 20 total fixed nodes in an area of 400 km^3

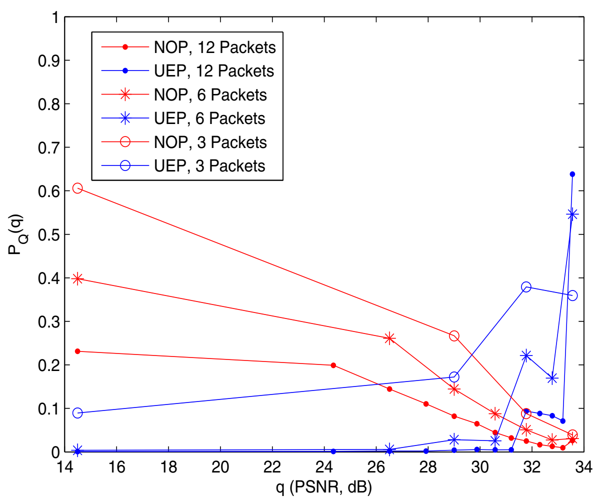


Figure 8. Quality PMF for systems with several packet length, with 53 total fixed nodes in an area of 400 km^3.

the probability of experiencing a PSNR of 34 dB. It means that there is a high probability of correctly receiving all the packets. On the contrary, when 49 nodes are considered (Fig. 8), the probability of having a PSNR equal to $[32-34]$ dB is less than 0.2 and a protection is required. Note that for low N values, the gain of the UEP compared to the *NOP* is considerably amplified, and the increasing of energy consumption and delay caused by a higher protection is justified. The tradeoff between quality vs. collision and delay is provided in Fig. 9, where the PSNR as a function of both the delay and the collisions is shown for a scenario with 25 mobile nodes. In the figure, rather than the average value, all the simulation outputs are provided. It can be seen that, when no protection is considered (red tone points), all the PSNR are achieved, even the lowest values. On the contrary, for an *UEP* level (blue tones) the

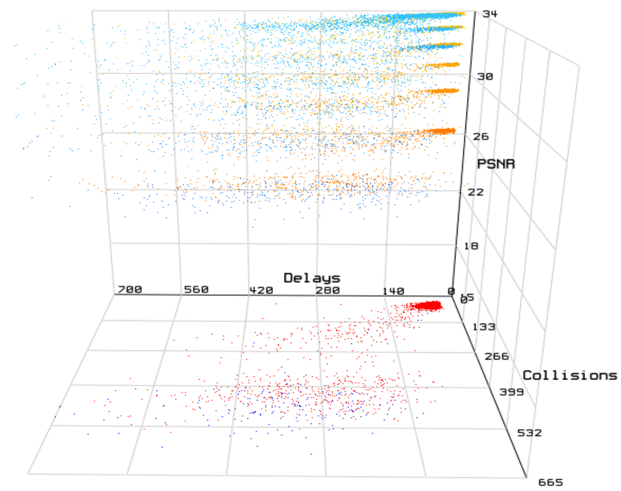


Figure 9. Tradeoff between quality vs. energy consumption and delay for a system with 25 mobile nodes, and 4 sinks, in an area of 400km^3. The red tone points are the results of NOP simulations, while the blue ones are the UEP output.

simulation results are mostly concentrated on the higher PSNR values. Moreover, note that the *UEP* scenario does not increase substantially the number of collisions or the delays of the networks.

In summary, an unequal protection, able to take advantage of the progressive nature of the source bitstream, outperforms systems with other protection levels or with no protection at all. Moreover, the more critical the scenario, the higher is the gain achieved from the *UEP*.

VI. Conclusion

Due to the limited condition of the underwater acoustic channel, high quality image transmission in underwater ad-hoc networks is an extreme challenging topic. In this work, starting from the Focused Beam Routing (FBR) algorithm, we proposed an optimized routing technique, able to maximize the quality of the received progressive image. Adopting a virtual unequal error protection (UEP), the algorithm is able to provide the required protection to each packet, rising the network congestion and delay only when strictly necessary. The results have shown that, by increasing the network density, the unequal error protection, able to take advantage of the progressive nature of the source bitstream, can outperform systems with equal error protection levels, improving the quality of the reconstructed image.

References

[1] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," *IEEE Journal of Oceanic Eng.*, vol. 25, no. 1, pp. 72–83, Jan 2000.

[2] W. Zhang, M. Stojanovic, and U. Mitra, "Analysis of a simple multihop underwater acoustic network," in *Proceedings of the third ACM international workshop on Underwater Networks*, San Francisco, California, USA, 2008.

[3] J. Kong, J. h. Cui, D. Wu, and M. Gerla, “Building underwater ad-hoc networks and sensor networks for large scale real-time aquatic applications,” in *MILCOM 2005*, 2005.
[4] I. S. Kulkarni and D. Pompili, “Coordination of autonomous underwater vehicles for acoustic image acquisition,” in *WuWNeT ’08: Proceedings of the third ACM international workshop on Underwater Networks*, 2008.
[5] A. Albanese, J. Blomer, J. Edmonds, M. Luby, and M. Sudan, “Priority encoded transmission,” *IEEE Trans. on Inform. Theory*, vol. 46, no. 6, pp. 1737–1744, Nov. 1996.
[6] A. E. Mohr, E. A. Riskin, and R. E. Ladner, “Graceful degradation over packet erasure channels through forward error correction,” in *Proc. IEEE Data Compression Conference*, Snowbird, UT, March 1999, pp. 92–101.
[7] R. Puri, K.-W. Lee, K. Ramchandran, and V. Bharghavan, “An integrated source transcoding and congestion control paradigm for video streaming in the Internet,” *IEEE Trans. on Multimedia*, vol. 3, no. 1, pp. 18–32, Mar. 2001.
[8] D. G. Sachs, R. Anand, and K. Ramchandran, “Wireless image transmission using multiple-description based concatenated codes,” in *Proc. SPIE*, vol. 3974, San Jose, CA, Jan. 2000, pp. 300–311.
[9] L. Toni, Y. S. Chan, P. C. Cosman, and L. B. Milstein, “Channel coding for progressive images in a 2-D time-frequency OFDM block with channel estimation errors,” *IEEE Trans. on Image Processing*, vol. 18, no. 11, pp. 2476–2490, Nov. 2009.
[10] Y. S. Chan, P. C. Cosman, and L. B. Milstein, “A cross-layer diversity technique for multicarrier OFDM multimedia networks,” *IEEE Trans. on Image Processing*, vol. 15, no. 4, pp. 833–847, April 2006.
[11] M. Zorzi, P. Casari, N. Baldo, and A. Harris, “Energy-efficient routing schemes for underwater acoustic networks,” *IEEE J. Select. Areas Commun.*, vol. 26, pp. 1754–1766, 2008.
[12] J. M. Jornet, M. Stojanovic, and M. Zorzi, “Focused beam routing protocol for underwater acoustic networks,” in *WuWNeT ’08: Proceedings of the third ACM international workshop on Underwater Networks*, 2008.
[13] B. Peleato and M. Stojanovic, “Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks,” *IEEE Commun. Lett.*, vol. 11, pp. 1025–1027, 2007.