Image transmission in Underwater Ad-Hoc Networks: Challenges and Initial Solutions

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***Abstract* — Due to its applications in marine research, oceanographic, and undersea exploration, underwater communication has been recently under intense investigation. Even though the applications in this field can be still considered frontier work, several studies have been recently reported. In this paper, we first provide an overview of the latest progresses in the undersea transmissions techniques, mainly focusing on autonomous underwater vehicles (AUV) ad-hoc networks. After introducing the potential and challenges of underwater communication, we highlight the state-of-the art techniques and algorithms which attempt to achieve underwater communications reliability. After assessing these techniques, it become clear how AUV networks suffer from major shortcomings when image transmission is considered. In this light, we finally propose two algorithms possibly able to improve the present limitations of image transmission performance in underwater networks.**

***Index Terms* — AUV, underwater communications, progressive images, cross-layer optimization, unequal error protection.**

I. INTRODUCTION

In the last decades, due to the increasing attention to undersea applications (i.e., oceanographic researches, exploration, offshore oil industry, etc.), underwater communications have been deeply investigated. Since the terrestrial radio link differs from its underwater counterpart, technology and communication models for the former might not be suitable for the marine scenario. Indeed, underwater communication technologies are mainly based on acoustic signal transmission, which present several 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.

While the general history of underwater communications has been already reviewed in a series of excellent papers [1] [2], here we specifically report the state-of-the art of AUVs ad-hoc network. We also provide an insight on some of the open issues and challenges in this field when multimedia[1] transmissions are considered. Even if in many applications (e.g., oceanographic) the interest in multimedia transmissions has been constantly growing, underwater communications have always been and still remain challenging due to low throughput, high path loss, and multipath degradation in underwater channels. To address this open issue, we propose two algorithms aimed at enhancing the quality of communication for images transmissions. The contribution of this paper is two-folds: (i) to provide an updated overview of the research in underwater communications, highlighting the limitation of existing approach to transmit reliably image and video bitstreams between AUVs (ii) to propose cross-layer optimization techniques for reliable progressive image transmissions.

The remainder of this paper is organized as follows: in Section II, an overview of ad-hoc underwater networks is provided. In Section III, a brief introduction to digital image coding is reported, mainly focused on progressive multimedia coding. In Section IV, requirements on the transmissions and cross-layer algorithms, aimed at optimizing multimedia transmission in AUVs networks, are presented. Finally, a brief summary and future works are reported in Section V.

II. AUVS AD-HOC NETWORKS

Undersea acoustic networks can be deployed with entirely fixed nodes (i.e., fixed-mounted devices), entirely mobile nodes (e.g., sensor involuntary moved by the water flow), or a mixture of the two (e.g., AUVs and fixed-sinks, buoys, as gateway to the surface). The topology of such networks, in which communicating nodes are possibly moving with respect to each other, usually follows the *ad-hoc* networks paradigm[2]: decentralized networks in which there is no *a priori* established infrastructure, but the nodes alone are responsible for multi-hop message relaying. In these self-configuring networks, each device is able to communicate to the destination through other possible devices (*relays*[3]).

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 [3]. Given that the path loss strictly

[1] Even though the multimedia communication usually includes both the image of video frames and the audio bitstream, from here onwards, we shall denote image and/or video (with no audio) transmission by multimedia communication.

[2] Although ad-hoc topology is usually considered in AUVs communication, also the concept of underwater acoustic cellular networks might be considered, as investigated in [3].

[3] Throughout this paper, we shall use node and relay interchangeably

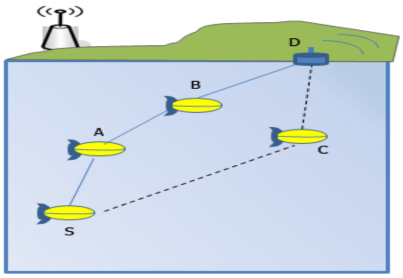

Figure 1: AUVs ad-hoc scenario

depends on both the central frequency and the link distance [4], 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 is the number of nodes, the greater are the transmission delay and the network complexity. The optimal tradeoff between reliability and energy consumption/delay was investigated in [5], where the authors, following a top-down approach, analyzed design challenges of each layer in the network protocol stack for underwater sensor networks.

In these mentioned studies, a good understanding of the communications channel is key to the design of communication systems, [6]. An exhaustive description of the channel modeling was provided in [7, 8], where the authors presented a stochastic model of shallow-water acoustic channel. However, the time-varying nature of the channel was not included. A recent channel model characterization made by Chitre [9] provides a physic-based channel model for shallow water in The model is based on ray acoustics and includes time-varying statistical effects as well as non-Gaussian ambient noise statistics observed during channel studies. Following this model, several techniques of channel equalization have been investigated to optimize *physical layer* techniques [10, 11]. Interfering signals mitigation through the use of an equalizer has been provided in [12]. Studies on coherent modulation techniques are reported in [13, 14], along with multicarrier modulation techniques [15], able to perform equalization in the frequency domain. Unfortunately, orthogonal frequency division multiplexing (OFDM) systems are extremely sensible to non uniform Doppler shift that results in each subcarrier. A simple solution was provided in [16], where non uniform Doppler compensation across subbands is performed using a single adaptively estimated parameter representing the Doppler rate.

Since underwater communications transmission is considerably more expensive (in terms of energy consumption) than the receiving process, a *MAC protocol* able to avoid frame collisions at the receiver is required. In [17] the authors proposed a MAC protocol based on the sleep scheduling, while the method presented in [18] is based on the hand-shake algorithm to avoid collisions. However, the energy consumptions and time required for the hand-shake protocol were not optimized. In [19], the authors proposed a distance aware collision avoidance protocol (DACAP): by employing different length hand-shake procedures, the protocol avoids the collisions from the node close to the sender, minimizing the average hand-shake duration at the same time. When a node receives a request-to-send (RTS) from a sender, it replies with a clear-to-send (CTS), becoming a candidate for relaying the information in the network. Then, the sender will transmit the packet only if it does not overhear other communications or if it does not receive any warning of overhearing from other nodes. Otherwise, it will defer the transmission. Since the node are half-duplex, the warning message can be lost if the sender has already started the transmission. However, the idle state of the transmission is chosen such as to avoid harmful collisions (i.e., collisions from closest nodes that might corrupt the transmission). Further details are provided in [19], where the authors demonstrated how the proposed algorithm is able to achieve a more than worthy throughput with low energy consumption.

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 [20-23]. In [23] 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. This routing algorithm might not achieve the best performance when image transmission is considered. In particular, the minimization of the energy consumption does not guarantee the minimization of the received image distortion. In some image coding techniques (e.g., progressive images), the loss of specific packets drastically compromises the decoding of the image. It follows that the reliable reception of these packets should be addressed with priority higher than the energy consumption. When a video transmission is considered, in order to guarantee a real-time decoding, the transmission delay and jitter should be addressed together with packets reliability. Since different applications lead to different constraints and goals, the optimal configuration studied in [23] should be reconsidered when multimedia transmission is the final application.

A dynamic scenario, more suitable for AUVs networks, has been investigated in [22] [21], where routing methodologies for both static and mobile nodes are provided. In [22], a vector-based forwarding routing is developed, which does not require state information on the sensors and only involves a small fraction of the nodes in routing. The proposed algorithm, however, does not consider and compare applications with different requirements. In [21], the dynamic routing protocol focused beam routing (FBR) is reported. Since in AUVs networks, each node can change its location, the proposed routing algorithm requires that each node is aware only of the location of its own and its final destination. By sending multicast RTS with a DACAP 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 are, if not already involved in any other communication, will reply with CTS, sending its own ID and location. Among the possible candidates, the sender will select one as its relay. The algorithm to select the best relay among many candidates is not exhaustively analyzed in the work, and it might be a critical aspect in underwater multimedia transmission.

In Fig. 1, a AUVs scenario is reported, where the node S needs to communicated to the surface through the node D. Rather than a direct link S-D, two multi-hop paths can be selected: S-A-B-D or S-C-D. The former leads to higher throughput than the latter, at the cost of higher delay and network congestion. When a high data rate transmission is considered (e.g., multimedia bitstream) a thigh constraint on the throughout must be satisfy and the S-A-B-D path might be preferred, due to the shortest link between each peer. It is clear that, to achieve the best performance from the system, the final application has to be taken into account. Although in [21] the authors demonstrated the efficiency of the proposed methodology for several networks sizes, the system performance when a multimedia transmission is considered as a possible application is still an open issue.

III. Progressive Images Transmission

In many underwater applications the interest in high quality image and video transmission has been growing. While sonar images can be sufficient for application aimed at detecting animals and their movement [24], 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. To face these issues, we aim using the progressive multimedia techniques, which allow partial decoding at various resolutions from a single compressed bitstream. We think that this is a promising technology for multimedia communications in underwater environments.

Progressive images have many attractive features [25, 26]. 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. As a drawback, since an error generally renders the subsequent bit useless, the transmission quality is highly sensible to channel impairments. 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. Unequal error protection is able to better protect the most important bits of the bitstream from channel impairments.

IV. Required and Proposed Algorithms

After presenting the characteristics of underwater communications in AUVs networks and introducing the progressive image coding technique, we present two proposed algorithms aiming at improving the image transmission reliability at the underwater receptor. Assessing the proposed techniques, it appears clear that the communication network optimization should take into account the specific requirements of the application to be deployed. In our case, it appears that the unequal error protection of progressive image bitstream is the main one. Therefore, we propose two approaches to deal with this problem.

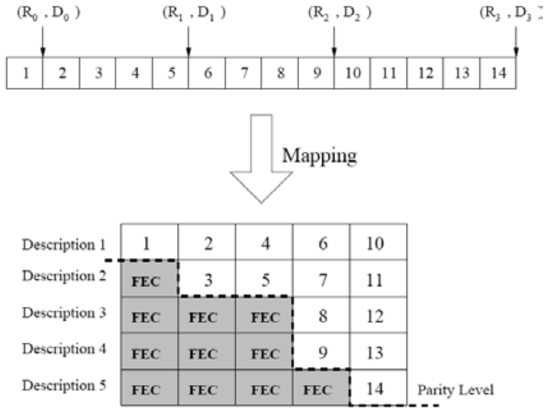

Figure 2: Illustration of the FEC-based MD coding technique.

A. Cross-Layer Unequal Error Approach

The progressive image features can be exploited by cross-layer coding algorithms [27, 28], based on optimal multiple description (MD) and unequal error protection (UEP) coding, able to take advantage of both physical and application layer diversity. The basic concepts of MD is to split contiguous information from the progressive bitstream into multiple descriptions approximately equally important, Fig. 2. During the MD mapping, additional protection can be included across the descriptions, based on the priority encoding transmission (PET)-like models (the more important the bits, the higher the protection). This coding scheme is sometimes referred to as symmetric n-channel FEC-based MD coding, able to generate multiple bitstreams such that each description individually describes the source with a certain level of fidelity. The main features of the MDs are that each description can be independently decoded and then combined with the other received MDs. The more descriptions are correctly received, the higher is the quality of the decoded image. Moreover, the corruption of one description does not jeopardize the decoding process of the correctly received descriptions.

FEC-based MD coding is successfully used to improve the performance of image transmission over terrestrial radio communications and could be a promising technique even in the underwater scenario. Each description can be sent over subbands in a multicarrier environment, or across several packets in a single carrier modulation system. The optimal UEP level can be evaluated according to the underwater channel model, the estimated Doppler values, the level interference and other parameter affecting the performance

B. Virtual Unequal Error Protection

Another approach aimed at protecting the transmission bitstram is the *virtual UEP* technique that is here proposed, associated to the aforementioned FBR routing algorithm. The normal behavior of the system would lead to the following transmission. Assuming that a progressive image is transmitted over N packets from the node S to the surface, the peer S will start a RTS/CTS procedure for each

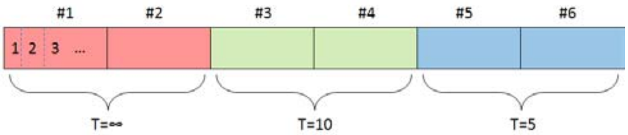

Figure 3: Virtual UEP

packet. When the RTS is sent, if no neighbor nodes are available, the node S will retransmit the RTS with a higher power level. After a maximum number of attempts (T), if not CTS are received from the node S, the current packet is discarded. It is obvious that, without optimizing this parameter, extremely low performance might be achieved when progressive image transmission is considered. Indeed, if the first packet is not correctly received, the whole image reconstruction is compromised.

To overcome this limitation, the parameter T (Maximum Number of Attempts) should be optimized for each packet transmission, taking advantage of the progressive nature of the bitstream. A degenerative case, with $T = \infty$ for all the packets, would guarantee the minimization of the reconstructed image. On the other hand, the energy consumption and delay of the network would increase accordingly. A tradeoff between image quality and network congestion is provided by this proposed virtual UEP algorithm: different T values are considered for each packet transmission, depending on the importance of its payload. The more important the bits in the packets, the higher is T, as shown in Fig. 3. The optimization should also investigate the packet size against the RTS/CTS overload and collisions.

V. SUMMARY

An overview of underwater network communication was provided, mainly focused on the autonomous underwater vehicles ad-hoc networks. Studies investigating several layer optimizations (physical, MAC, network and application layer) are reported, highlighting their weakness for image and video applications. We have proposed the progressive image coding as a potential solution for underwater image. Finally, we have proposed two possible algorithms to encode the progressive images and the acoustic frames and control the transmission to reach the required reliability at the receptor. Our future works will be to evaluate these algorithms to highlight their benefit.

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