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Collaborative hybrid ARQ for CDMA-based reliable underwater acoustic communications

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Collaborative Hybrid ARQ for CDMA-based Reliable Underwater Acoustic Communications

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***Abstract*—Achieving high throughput and reliability in underwater acoustic networks is a challenging task due to the bandwidth-limited and unpredictable nature of the channel. In a multi-node structure, such as in the Internet of Underwater Things (IoUT), the efficiency of links varies dynamically because of the channel variations. When the channel is not in good condition, e.g., when in deep fade, channel-coding techniques fail to deliver the required information even with multiple rounds of retransmissions. An efficient and agile collaborative strategy among the nodes is required to assign appropriate resources to each link based on their status and capability. Hence, a cross-layer collaborative strategy is introduced to increase the throughput of the network by allocating unequal share of system resources to different nodes/links. The proposed solution adjusts the physical- and link-layer parameters in a collaborative manner for a Code Division Multiple Access (CDMA)-based underwater network. An adaptive Hybrid Automatic Repeat Request (HARQ) solution is employed to guarantee reliable communications against errors in poor communication links. Results are being validated using data collected from the LOON underwater testbed, which is hosted by the NATO STO Centre for Maritime Research and Experimentation (CMRE) in La Spezia, Italy.**

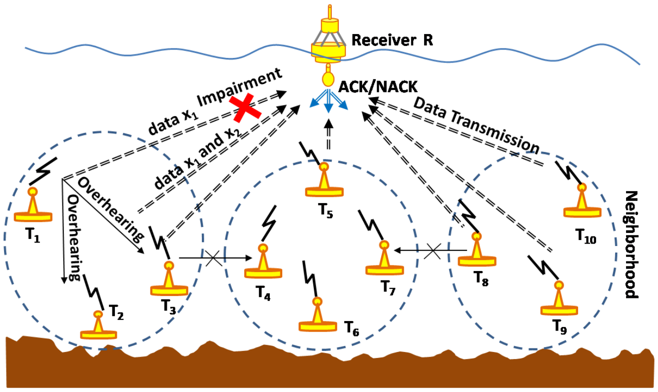

Fig. 1: Architecture showing transmitting nodes, $T_i, i = 1, ..., N_m$ in neighborhood m, $m = 1, ..., M$, when the channel quality varies from one link to another. As an example, data from node $T_1 \in N_1$ fails to reach the receiver. CDMA is exploited as the multiple access technique. The nodes overhear and collaborate in the HARQ procedure based on their communication links quality to improve the system throughput.

I. INTRODUCTION

Overview: Underwater Acoustic Networks (UANs) face many challenges due to the unique and harsh characteristics of the underwater propagation of acoustic waves [1]–[4]. In applications as the Internet of Underwater Things (IoUTs), data is usually distributed across multiple nodes, while a single node (sink) is used for data collection, fusion, and processing [5]–[7]. To maximize the net throughput of the network, one of the major challenges is the design of a secure, robust, and scalable Medium Access Control (MAC) and an Error Control (EC) strategy, while guaranteeing fairness among competing and/or collaborating nodes [8]–[11].

Motivation: Code Division Multiple Access (CDMA) is a promising physical-layer and multiple-access technique for UANs since i) it is robust to frequency-selective fading, ii) it compensates for the effect of multipath at the receiver by using filters that can collect the transmitted energy spread over multiple paths, and iii) it allows receivers to distinguish among signals simultaneously transmitted in the same frequency band by multiple devices [12]–[14]. The use of an efficient CDMA scheme, supporting an adaptive EC strategy such as Hybrid Automatic Repeat Request (HARQ), can therefore increase network reliability and throughput. Various works have been proposed addressing separately CDMA and HARQ for UANs. Authors in [13] discuss Direct-Sequence Spread Spectrum (DSSS) CDMA as a candidate MAC for mobile UANs in which multiple nodes connect to a central receiver. In [15], the authors applied fountain codes to HARQ in underwater networks to reduce retransmissions and achieve optimal broadcasting policies. In [16], we proposed a scheme based on HARQ that exploits the diversity gain offered by independent links of an underwater acoustic Multiple Input Multiple Output (MIMO) channel.

Contribution: In this short paper, we extend the concept of point-to-point HARQ to an implicitly collaborative scenario in combination with a DSSS-CDMA approach. A transmitting node with low-quality communication links piggybacks its neighboring nodes when protecting its data against the errors, so that the system throughput increases. We propose a solution to achieve the following objectives: i) high network reliability and throughput by allocating appropriate share of system resources to different nodes; ii) latency problem alleviation caused by the conventional HARQ retransmission strategy; iii) simultaneous transmission on the available bandwidth via easily- and locally-generated CDMA chaotic codes using a secret seed with a flexible and large family size; and iv) low energy consumption via efficient output power allocation. Our method is able to achieve these four objectives in *shallow-water* communications (depth less than 100 m)—which may be heavily affected by multipath—and dynamically finds the optimal trade-off among these objectives according to the application requirements.

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II. PROBLEM DEFINITION AND PROPOSED SOLUTION

The use of chaotic sequences in CDMA guarantees secure communications. Albeit deterministic, chaotic codes look like noise, similarly to Pseudo-Noise (PN) sequences; however, they are different for every bit of transmitted data. Hence, it is much harder for an eavesdropper, i.e., an unauthorized node without the knowledge of the used codes (seed plus generating map), to regenerate the sequences and extract the data. This property allows us to assign authorized nodes to collaborate in the defined scenario or to remove others, to secure the communication, and to guarantee the service to a large number of users. Yet, CDMA requires to optimize the transmit power and spreading code length to limit the near-far problem and to maximize system throughout.

In practical scenarios and in the truncated HARQ, the number of retransmissions is limited. If the quality of the underwater channel can not be guaranteed, retransmissions may be not sufficient to deliver correctly the intended data, thus detrimentally affecting the throughput of the network. Figure 1 shows the case in which N transmitting nodes, $T_i,\ i = 1, 2, ..., N_m$, in neighborhood areas $m,\ m = 1, ..., M$ combine independent sensed information, $x_i(r)$ (from independent nodes) for data fusion at the receiver R (the sink) at different transmission rounds $r,\ r = 1, 2, ..., r_T$. Nodes in the same neighborhood can overhear other transmissions and collaborate to deliver the intended data, similarly to what T_2 is doing for T_1 in Fig. 1.

The proposed collaborative HARQ for data protection, combined with a CDMA (using chaotic codes) for secure and interference-free transmissions, relies on a closed-loop strategy based on measurements sent back by the receivers. This is to avoid relying on the unrealistic symmetric-link assumption, which does not usually hold in the underwater environment. Each receiver periodically collects information on the channel state. This information is then provided to the neighbors by transmitting short ACK/NACK messages.

The error probability P_e on the decoded codeword $\tilde{x}_i$ for the transmitted codeword x_i can be upper-bounded using the *Bhattacharyya bound* [17], [18] as, $P_e\big(x_i(r), \tilde{x}_i(r)\big) \leqslant B_i^h$, where h is the Hamming distance and B is the Bhattacharyya Parameter (BP) in a noisy channel. This parameter is defined for every transmitted bit x and received bit y as $B = \sum_{y\in\Omega} \sqrt{\Pr(y|x = 0)\Pr(y|x = 1)}$. Here, Ω stands for the output alphabet and $\Pr(y|x = 0)$ and $\Pr(y|x = 1)$ are transition probabilities, $\forall y \in \Omega$. This parameter is considered as a channel reliability metric as it is an upper-bound on the probability of error in a typical Maximum-Likelihood (ML) detection problem, where larger BP values suggest channel unreliability and vice versa. The union-Bhattacharyya bound [18] can be calculated for each point-to-point channel as, $P_{e\,i}^c \leqslant \sum_{h'=1}^{n} A_{h'} {B_i}^h$, where $P_{e\,i}^c$ denotes the codeword error probability of code c from family code $\mathbb{C}$ and $A_{h'}$ represents the codewords with weight h'.

The other promising metric is the *long-term throughput*, which is defined based on the renewal reward theorem [19] as $\eta = \mathbb{E}[\tilde{X}]/\mathbb{E}[\tilde{T}]$. Hence, $\mathbb{E}[.]$ defines the expectation of a random variable, $\mathbb{E}[\tilde{X}] = X\big(1 - \Pr_{out}(r)\big)$ is the number of decoded information nats, i.e, natural information unit. $\Pr_{out}$ can be defined as the probability that the data has not been decoded in a specific round r. $\mathbb{E}[\tilde{T}]$ is the number of attempts for channel use during a packet transmission period. We decrease $\Pr_{out}$ via node collaboration and by adjusting the corresponding parameters so as to improve the network long-term throughput. In a DSSS-CDMA system, the error probability of a coded packet can be upper-bounded as [17],

$$P_{e\,i}^c \leqslant (2^k - 1) \cdot Q\left(2\sqrt{\frac{P_i}{J_i} SL_i\, R_{ci}\, d_i}\right), \tag{1}$$

where P_i is the transmitting power of T_i, $Q(.)$ is the Q-function, J_i is the total interference and noise experienced by T_i, $R_{ci} = k/n$ is the coding rate of a code $c(n, k)$, d_i is the smallest hamming distance h_i, and SL_i is the length of CDMA spreading code. Note that (1) implies that the transmitted power, amount of interference, rate, strength of channel coding, and the processing gain of CDMA system, all affect the codeword probability of error.

The maximum achievable spectral efficiency achieved by each node in a neighboring area m, in bps/Hz, at round r is,

$$R_i(r) = \log\left(1 + \frac{\alpha_i P_i g_i}{N_0 W + \sum_{j=1, j\neq i}^{N_m} \alpha_j P_j g_j}\right), \tag{2}$$

where W is the channel bandwidth, N_0 is the noise Power Spectral Density (PSD), g_i is the channel gain, and α_i represents the power control coefficient. To maximize the total rate and to satisfy the performance and energy consumption constraints, we cast an optimization problem to find the optimum parameter vector $\Theta = [\theta_1, ..., \theta_{N_m}]$, where $\theta_i = [P_i, R_{ci}, d_i, SL_i, \alpha_i]$ and $i = 1, ..., N_m$.

$$\max_{\Theta}\ \mathcal{F}(r) = \sum_{i=1}^{N_m} R_{ci} R_i(r) \tag{3a}$$

$$\text{s.t.}\ \ \gamma_i(r) = \big(2SL_i\big)_{dB} + \big(R_{ci} d_i\big)_{dB} + \big(\frac{\alpha_i P_i g_i}{J_i}\big)_{dB} \geq \gamma_{min}, \tag{3b}$$

$$\sum_{i=1}^{N_m} \alpha_i P_i g_i \leq P_{th},\ \ P_i \in [0, P_{max}],\ \sum_{i=1}^{N_m} \alpha_i = N_m, \tag{3c}$$

where $\gamma_i(r)$, in dB, is the received Signal-to-Interference-Noise-Ratio (SINR) from T_i at round r, $J_i = N_0 W + \sum_{j=1, j\neq i}^{N_m} \alpha_j P_j g_j$, and γ_{min} is the minimum SINR, which is proportional to the probability of error in HARQ and determines the level of performance. P_{th} guarantees that the total received power in m does not affect other neighborhoods.

Let $\Psi = [\psi_1, ..., \psi_L]$ be the vector of Lagrange multipliers and L be the number of constraints. We form the Lagrangian function as follows,

$$\mathcal{L}(\Theta, \Psi) = -\mathcal{F} - \sum_{l=1}^{L} \psi_l (g_l(\Theta) - b_l), \tag{4}$$

where each $g_l(\Theta)$ and b_l are determined by each constraint such that $g_l(\Theta) \leq b_l$. To find the optimum values, $\bigtriangledown_{\Theta} \mathcal{L}(\Theta, \Psi) = 0$ should be solved. There are L complementary equations that should be held as $\psi_l\big(g_l(\Theta) - b_l\big) = 0,\ l = 1, ..., L$, such that $\psi_l \geq 0$. The feasible results of these equations determine the optimum parameter that results in maximum spectral efficiency.

Algorithm 1 Collaborative HARQ for nodes $T_i \in \mathcal{N}_m$

```
1:  $\forall i = 1, ..., N_m$ : $r_i \leftarrow 1$ as the index of transmission round
2:  if Event (request to send for $T_i \in \mathcal{N}_m$ ) then
3:      while time-out codeword( ) do
4:          $\forall T_i$: Make the packets; Generate chaotic code
5:          Solve problem (3); Event (wait for $\mathrm{ACK_i}/\mathrm{NACK_i}$)
6:          while $\mathrm{NACK_i}$ AND $r_i \leqslant r_T$ do
7:              $r_i \leftarrow r_i + 1$; HARQ Retransmission procedure( )
8:          end while
9:          for $\forall$ $T_{\widehat{i}}(r_T)$ (impaired nodes) do
10:             $P_{\widehat{i}} \leftarrow 0$; solve (3) for new $\Theta_j^*$
11:             $\hat{c} \leftarrow \arg\max \{\mathrm{R_j}\}_{\mathrm{j} \neq \widehat{\mathrm{i}}}$; Update $\sum R_{\widehat{c}}$ % $\hat{c}$ : collaborator
12:             if $R_{\widehat{i}} < \sum R_{\widehat{c}}$ then
13:                 Choose nodes $T_{\widehat{c}}$ as the collaborator
14:                 else Store $\sum R_{\widehat{c}}$; Find next $\widehat{c}$ by executing step 11
15:             end if
16:         end for
17:         repeat steps 2-8 until $\mathrm{ACK_i}$      % the new collaboration
18:     end while
19: end if
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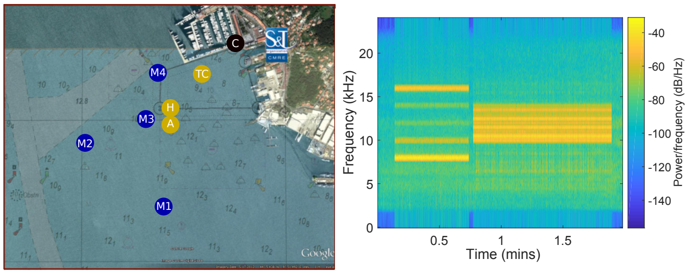
Algorithm 1 reports the pseudo-code executed by sender nodes $T_i \in \mathcal{N}_m$. In the conventional scheme, if T_i does not receive the ACK before a timeout expires, it will keep transmitting extra information in the next packets under the HARQ policy considering the previous channel state. However, in the proposed scheme, because of the collaboration among the nodes (i.e., $T_{\widehat{c}}$), the probability of reception is increased leveraging independent channels (channel diversity).

III. Performance Evaluation

Testbed: The CMRE Littoral Ocean Observatory Network (LOON) [20] is a testbed permanently deployed at sea close to the CMRE premises (in the Gulf of La Spezia, Italy, Fig. 2(I)) for underwater communications and networking. It consists of four bottom-mounted tripods (M1-M4) installed at a depth of about 10 m. Each tripod is equipped with heterogeneous communications technologies and sensors, and it is cabled to a shore control station (C) providing data connection and power supply. The LOON tripods also support arbitrary waveform transmission/recording. Additionally, the LOON includes a high-definition acoustic data acquisition system (at frequencies above 1 kHz) from an array of hydrophones (H), a thermistor chain (TC), sound velocity sensors, an Acoustic Doppler Current Profiler (ADCP) with waves measurement (A), and a meteorological station. These sensors are used to correlate the characteristics of the acoustic channel with the performance of the investigated protocols. The LOON provides therefore a comprehensive data set of environmental, acoustic, and packet measurements to study the communication processes at different communication layers.

Experiment Settings: A variety of scenarios can be considered in the shallow-water environment where the LOON is deployed to capture outputs of the proposed system. We considered a point-to-point transmission from node $M4$ to H for modeling the link of several rounds of transmissions. Packets are transmitted using baseband Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) modulations over the passband channel $4-19$ kHz by exploiting Reed-Solomon channel coding $(7,3)$ or $(15,9)$. A logistic map is used to generate a chaotic spreading code with various lengths, i.e., $SL = [10, 40]$. As an example, we have measured the average Signal-to-Noise Ratio (SNR) equal to 32.68 dB for a QPSK transmitted signal with $SL = 22$, while the average Bit Error Rate (BER) of approximately 4.6365×10^{-4} is achieved.



(I) (II)

Fig. 2: (I) Geographic configuration of the LOON testbed, in the Gulf of La Spezia, Italy. (II) Spectrum of a sample received signal from the LOON in two successive transmission time slots while the spreading length and coding rate have changed.

Simulation Settings: We focus on the collaboration among the nodes in transmission and assume that ACK/NACK feedback links are free of errors. However, Algo. 1 has a mechanism with a timer to retransmit the data if the feedback is not received (or its noisy) within the expected time. Nodes in the same neighborhood can overhear each other, while nodes in adjacent areas do not receive the data since the chaotic CDMA sequence protects from unauthorized overhearing. Simulation are conducted for a neighborhood of 3 nodes. We use the data collected using the LOON to model a multiuser scenario, then we optimize the parameters, as in Sect. II. The computed values are passed through the channels extracted from the LOON in a close-loop manner. We evaluate the system performance in MATLAB by considering the following metrics: SINR, long-term throughput (η), neighborhood efficiency rate, and effective rate per node.

Results: Figure 2(II) shows the frequency spectrum of a sample received signal from the LOON while the spreading length and coding rate changes for two successive transmitted signals. In Figs. 3(I) and 3(II), two experiments with different settings are shown (for BPSK and QPSK scenarios, respectively). The PSD of the transmitted and received signals in passband and decoded baseband are plotted for comparison. Received SNR versus bandwidth, channel profile for the duration of the transmission, and scatter plot of the estimated symbols are provided. The transmitted signal parameters, BER, and SNR are also included in the figure. In Fig. 4(I), the received SINR in a neighborhood of three nodes is presented to investigate the effect of multiuser interference. Figure 4(I-a) presents the case where only one node in the area is transmitting. In this case, without interference, the received signal has a considerably better SINR. In Fig. 4(I-b), the data transmission in the area is performed by three nodes, so there is a multi-user interference. Figure 4(II-a) depicts the total efficient rate in a neighborhood of three nodes. The plot shows how the collaboration strategy handles channel impairments and distributes the traffic load in the neighborhood. As the result of collaboration, when there are fewer nodes to perform data transmission, multiuser interference drops and spectral efficiency improves. Figure 4(II-b) presents the effective received rate per node. The plot shows that in the case where an impairment occurs in T_1 link, T_2 collaborates in

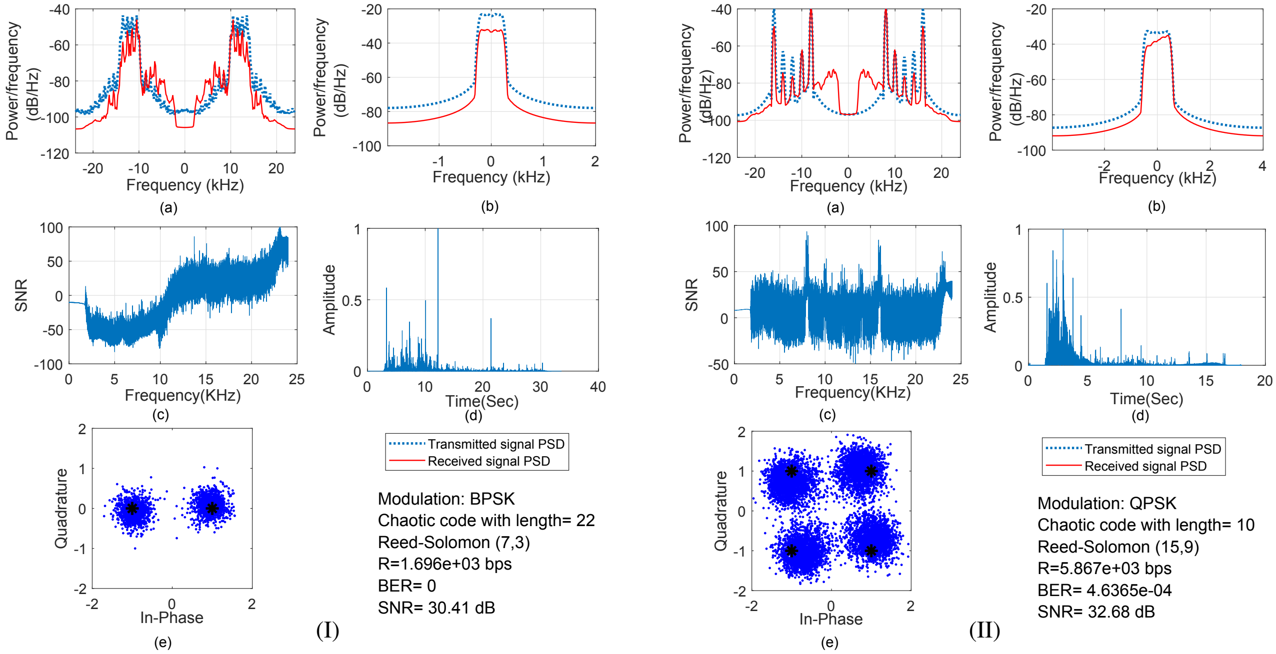


Fig. 3: (I) and (II) show two experiments with different parameters; (a) Power Spectral Density (PSD) of the transmitted and received passband signals; (b) PSD of the baseband decoded received signal in comparison with transmitted signal; (c) Signal-to-Noise Ratio (SNR) of the received signal per frequency; (d) Experienced channel profile; (e) Constellation of the equalized baseband received signal.

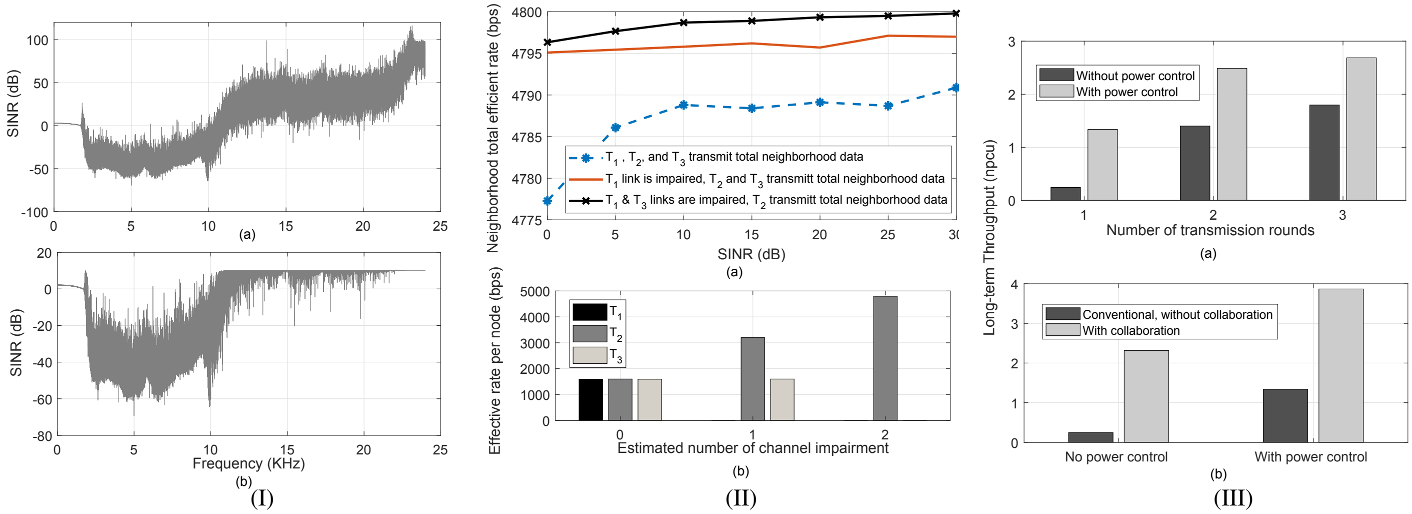


Fig. 4: (I) SINR (simulation) when the number of transmitting nodes in a neighborhood is (a) one; (b) three. (II) (a) Efficient rate of the neighborhood; (b) Effective rate per transmitting node with channel impairments. (III) Long-term throughput in nats-per-channel-use (npcu) (a) for different maximum number of transmission rounds when no channel impairment occurs and with/without power control; (b) comparing traditional HARQ with our collaborative method, with/without power control.

data transmission. In Fig. 4(III), long-term throughput for the proposed collaborative method is investigated. In Fig. 4(III-a), η is plotted for different values of r_T when none of the nodes experiences channel impairment. The plot confirms that power control can improve the long-term throughput. Finally, in Fig. 4(III-b), collaborative HARQ is compared with the conventional method to confirm that collaboration improves long-term throughput under channel impairment. The figure also shows the positive effect of power control.

IV. CONCLUSIONS AND FUTURE WORK

We introduced a collaborative strategy for a CDMA-based underwater Hybrid ARQ to increase the overall throughput of the network. Our solution leveraged both chaotic CDMA and HARQ properties to adjust the physical- and link-layer parameters and to compensate for the poor underwater acoustic communication links. System performance improvement and power control were considered, while the total throughput of the system was optimized. Experimental data was collected on the CMRE LOON testbed and used to extend the results to other nodes via simulation. As future work, we plan to implement our solution on a larger underwater network with heterogeneous nodes to manage a higher volume of data and to analyze the scalability of the solution. Furthermore, the errors in the feedback ACK/NACK links will be taken into account.

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Abstract

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Keywords

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