Dynamic Coded Cooperative ARQ for Multi-hop Underwater Acoustic Networks

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***Abstract*—Dynamic coded cooperation (DCC) does not need extra transmission time scheduled for the relay, which is appealing to the bandwidth-limited high-delay underwater acoustic (UWA) environment. In this paper, we propose dynamic coded cooperative automatic repeat request (DCC-ARQ) protocol for multi-hop UWA networks. A transmission packet with multiple blocks is taken as a one-shot unit, where an erasure-correction code is used for inter-block encoding. Adopting the DCC scheme in each hop UWA transmission, the half-duplex cooperative node switches to cooperation phase immediately after it decodes the cooperative message, which provides a more reliable cooperative path for the specific three-node network. Further, if the relay (or destination in the last hop) node sends a negative acknowledgement (NACK) to the upstream cooperative node, the cooperative node only needs to retransmit parts of the packet under DCC-ARQ mechanism, hence a reduced end-to-end transmission latency can be achieved. Simulation results show that for a one-shot transmission, the proposed protocol achieves good balance between the reduced end-to-end delay and decent outage performance, relative to existing protocols.**

***Index Terms*—Coded cooperation, OFDM, dynamic coded cooperation, ARQ, underwater acoustic communications.**

I. Introduction

Underwater Acoustic (UWA) networks are experiencing a rapid growth, due to their high relevance to commercial and military applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance [1], [2]. However, the design of efficient communication protocols for UWA networks is still an open research problem due to the unique characteristics of the UWA communication channel such as limited bandwidth, high and variable propagation delays, and significant multipath and scattering.

To establish reliable UWA communication, the automatic repeat request (ARQ) protocol that organizes the retransmission of erroneous packets is required. However, as the long propagation delays in UWA channels, various improved efficient ARQ schemes [3]–[7] have been proposed for UWA networks. One of the interesting protocols named cooperative ARQ scheme [4] is that, the retransmission happened from the cooperative node instead of that from the source node after the destination sent the negative acknowledgement (NACK). As the cooperative diversity gain, this cooperative retransmission can significantly increase the probability of successful retransmission.

For the relay-based cooperative communications, multiple relay strategies can be applied, e.g., amplify-and-forward (AF), decode-and-forward (DF) and compression-and-forward (CF) [8], [9]. Further, coded cooperation (CC) [10] applying channel coding to relay cooperation was studied as a practical protocol, in which each user tries to transmit incremental redundancy for its partner. Recently, dynamic coded cooperation (DCC) [11]–[13] has been proposed by investigating turbo- and low-density parity-check codes (LDPC)-coded relay cooperation. We proposed orthogonal-frequency-division multiplexing (OFDM) modulated DCC scheme for UWA channels in [14], which is particularly appealing to UWA networks where a relay node with abundant resources (e.g., a surface buoy) can enhance communications among underwater nodes without changing their transmission procedure.

Fig. 1 shows the main difference of conventional DF-, CC-, and DCC-cooperation schemes on bandwidth efficiency [15]. We can find that there is no extra transmission time scheduled for the relay with the DCC scheme, making it bandwidth efficient. The source can be even unaware of the existence of the relay in the DCC scheme.

In this paper, we combine DCC with cooperative ARQ, termed as the DCC-ARQ protocol, for multi-hop UWA networks. Similar to [16], a transmission packet with multiple blocks is taken as a one-shot unit, where an erasure-correction code is used for inter-block encoding. In per-hop transmission, we assume that the cooperative path is pre-determined by the optimal algorithm, forming a specific three-node network. With or without retransmission, the DCC-ARQ protocol can get benefits on both of the two kinds of cases.

- The half-duplex cooperative node switches to cooperation phase immediately after it decodes the cooperative message, offering both coding gain and diversity gain, which provides a more reliable cooperative path for the specific three-node network.
- When the relay (or the destination in the last hop) node receives an erroneous packet, it asks for retransmission from a cooperative node, which is selected in the cooperative region. During the retransmission phase, the cooperative node only needs to retransmit parts of the packet under DCC-ARQ mechanism, hence a reduced end-to-end transmission latency can be achieved.

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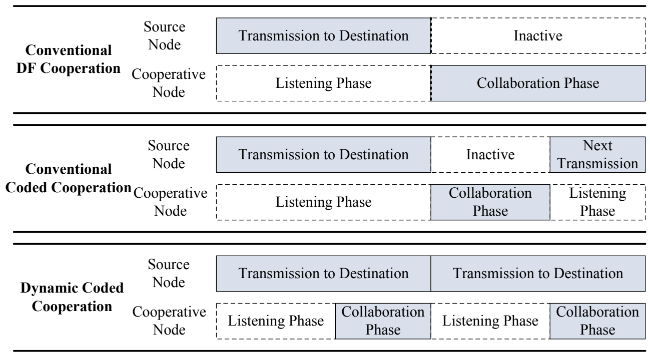


Fig. 1. Bandwidth efficiency for different cooperative schemes [15].

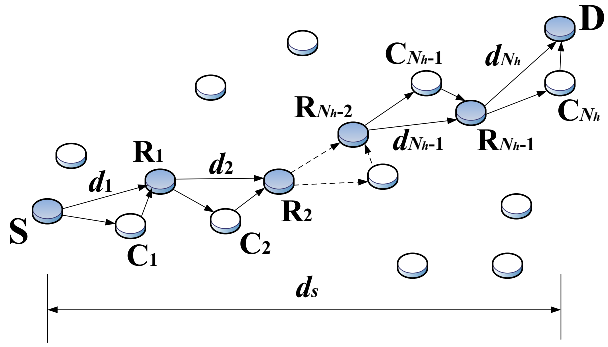


Fig. 2. An example of N_{h}-hop UWA network adopting the DCC scheme.

The rest of this paper is organized as follows. Section II presents the proposed DCC-ARQ protocol for multi-hop UWA networks. Section III contains simulation results for a one-shot transmission in a 5-hop UWA network, and conclusions are contained in Section IV.

II. The Proposed DCC-ARQ Protocol for Multi-hop UWA Networks

Consider an N_{h}-hop UWA network, as shown in Fig. 2, where the first node indexed by 0 is the source, and the last node indexed by N_{h} is the destination. Assuming that the routing path is pre-determined by the optimal routing algorithm for a given source-destination pair. In the i-th hop, we select the best node in the cooperative region as the cooperative node the same as in [4], and define it as the i-th cooperative node helping the (i-1)-th relay node transmitting data to the i-th relay. Fig. 3 shows a cooperative region example with two-hop scenario.

A. Dynamic Coded Cooperative ARQ Protocol

We assume a burst-based transmission. Each burst consists of N_{bl} blocks, which can be an orthogonal-frequency-division-multiplexing (OFDM) block as an example. An erasure-correction channel code is applied over the N_{bl} blocks for the inter-block encoding.

To illustrate the dynamic coded cooperative ARQ protocol, we will first briefly introduce the traditional ARQ protocol and the cooperative ARQ protocol in [4], as shown in Figs. 4

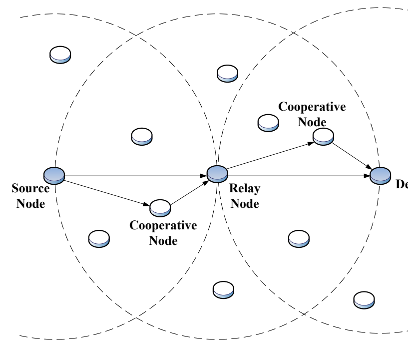


Fig. 3. Cooperative region for multi-hop UWA networks adopting the DCC scheme.

(a) and (b). In each hop transmission, if the receiver can not decode the message correctly, it asks for retransmission with a NACK signal to the transmitter under the traditional ARQ protocol, and to the cooperative node under the cooperative ARQ protocol. Obviously, the later protocol can provide a more reliable retransmission path since the cooperative node lies between the transmitter and the receiver. Additionally, it also saves the propagation delay because of the shorter node-to-node distance.

For the DCC-ARQ protocol, to get a reliable transmission in each hop, it takes the following steps.

- *Instantaneous transmission upon successful decoding*: During the listening phase for the cooperative node, it attempts burst decoding and performs parity check when receiving one more block; immediately after the information bits within one burst are successfully recovered, say N_{li} blocks, it regenerates the coded transmission blocks, say $N_{\mathrm{coop}} := N_{\mathrm{bl}} - N_{\mathrm{li}}$ blocks, and switches to cooperative phase and relays the message to the downstream node.
- *Partial retransmission upon dynamic decoding*: If the retransmission is asked, the cooperative node will only retransmits the first N_{li} blocks as shown in Fig. 4 (c), instead of the all N_{bl} blocks as the cooperative ARQ scheme in [4].
- *Joint decoding both before and after the retransmission*: Before retransmission, the receiver node will do joint decoding based on the N_{bl} blocks from the transmitter node with the last N_{coop} blocks superimposed by the relay's transmissions; After the retransmission, the additional N_{li} blocks will be used together with the previously available N_{bl} blocks for joint decoding.

We should highlight that, with the extremely poor channel link quality, the DCC-ARQ protocol would not start cooperative phase, i.e., $N_{\mathrm{li}} = N_{\mathrm{bl}}$. Then the DCC-ARQ protocol becomes the cooperative ARQ protocol. Further, the proposed DCC-ARQ protocol is appealing for UWA networks, but also applicable to terrestrial radio communications.

B. Decoding at the Relay Node

For UWA transmissions, we assume that each hop uses OFDM modulation [17]. Given a three-node UWA network in

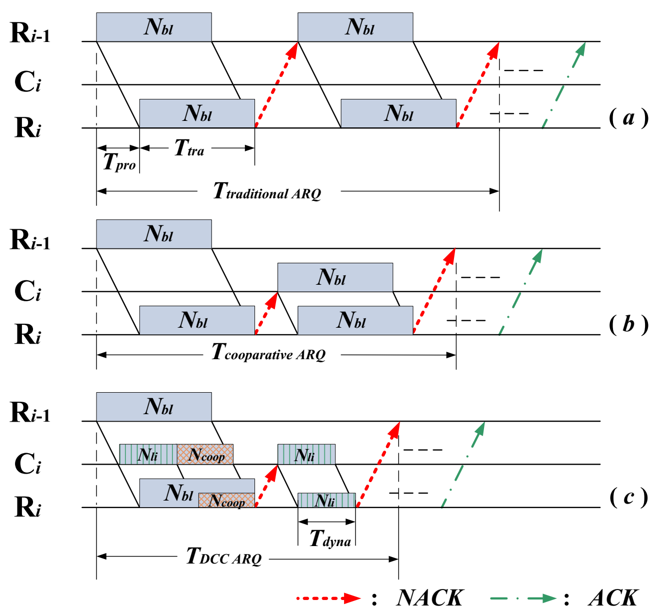


Fig. 4. Illustration of several ARQ protocols in per-hop UWA network. (a) Coded traditional ARQ; (b) Coded cooperative ARQ; (c) Dynamic coded cooperation (DCC) ARQ. To compare with the proposed DCC-ARQ protocol, both traditional ARQ and cooperative ARQ protocols are equipped with erasure-correction channel code.

the i-hop, we have investigated two cooperation strategies in [14], named repetition redundancy (RR) and extra redundancy (ER) for the DCC scheme, where the cooperative node transmits either identical or different OFDM blocks as the $(i-1)$-th relay node during the cooperation phase. Let N_{r} denote the number of receiving elements at the destination. Consider an OFDM modulation with K subcarriers, and assume a time-invariant scenario. During the cooperation phase, the destination (the i-th relay node) receives the superposition of the signals from the source (the $(i-1)$-th relay node) and the cooperative node. The RR cooperation strategy can be described briefly as bellow.

Since the cooperative node transmits identical OFDM blocks as the source, the input-output relationship of the lth received OFDM block at the νth receiving element is

$$\begin{aligned} z_{\nu,l}[k] &= \underbrace{\left(H_{\nu,l,\mathrm{sd}}[k] + H_{\nu,l,\mathrm{cd}}[k]\right)}_{:=H_{\nu,l}[k]} s_l[k] + n_{\nu,l}[k], \\ &= H_{\nu,l}[k] s_l[k] + n_{\nu,l}[k], \end{aligned} \tag{1}$$

where $H_{\nu,l,\mathrm{sd}}[k]$ denotes the channel frequency response between the source and the destination, $H_{\nu,l,\mathrm{cd}}[k]$ denotes the channel frequency response between the cooperative node and the destination, and $n_{\nu,l}[k]$ is the ambient noise.

Assuming $n_{\nu,l}[k] \sim \mathcal{CN}(0, \sigma^2_{\nu,l})$ and all the constellation symbols are equal-probable, the *a posteriori* probability (APP) of the kth data symbol in the lth OFDM block during the demodulation step is

$$p\left(s_l[k] \middle| \{z_{\nu,l}[k]\}_{\nu=1}^{N_{\mathrm{r}}}\right) \propto \exp\left\{-\sum_{\nu=1}^{N_{\mathrm{r}}} \frac{\left|z_{\nu,l}[k] - H_{\nu,l}[k] s_l[k]\right|^2}{\sigma^2_{\nu,l}}\right\}. \tag{2}$$

C. End-to-End Delay

Before discussion on the end-to-end delay for the cooperative multi-hop UWA networks, we adopt the following assumptions for each hop transmission.

- The ACK signals will always be sent to the transmitter, and the NACK signals will be sent to the cooperative node and transmitter node alternately, which can be controlled by the response mechanism at the node. For example, if the receiver can not decode the packet correctly at the first time, the NACK signal will be sent to the cooperative node and let it do retransmission. Then the receiver node will decode again and send ACK or NACK to the transmitter node. This is so called a "full cycle". With this assumption, the retransmission propagation delay depends on the retransmission index is odd or even.
- The ACK or NACK signal can always be received by the cooperative nodes or the transmitter nodes, and both of them will always respond to these feedback signals. Hence we will skip the time-out cases in this paper.

The end-to-end delay for the N_{h}-hop UWA network is

$$T_{\mathrm{e2e}} = \sum_{i=1}^{N_{\mathrm{h}}} T_{\mathrm{i,e2e}}. \tag{3}$$

For the i-th hop, the end-to-end delay consists of the transmission latency and the propagation delay

$$T_{\mathrm{i,e2e}} = T_{\mathrm{i,pro}} + T_{\mathrm{i,tra}}, \tag{4}$$

where the propagation delay $T_{\mathrm{i,pro}}$ is related to the retransmission times, the end-to-end distance, the sound speed in water, and different cooperative schemes.

In each hop, let T_{pro} be equal to the end-to-end distance divided by the sound speed in water, N_{reTra} be the retransmission times. Then for the traditional ARQ protocol as shown in Fig. 4, we have

$$T_{\mathrm{Tradi,i,e2e}} = (2T_{\mathrm{pro}} + T_{\mathrm{tra}})(1 + N_{\mathrm{reTra}}), \tag{5}$$

where T_{tra} is transmission time of a burst data. Denote T_{bl} as the block time-duration, it can be written as

$$T_{\mathrm{tra}} = N_{\mathrm{bl}} T_{\mathrm{bl}}. \tag{6}$$

For the cooperative ARQ and DCC-ARQ protocols, we have

$$T_{\text{Coop-odd,i,e2e}} = (3T_{\text{pro}} + 2T_{\text{tra}})\frac{N_{\text{reTra}}+1}{2} \quad N_{\text{reTra}} = 1, 3, 5, \cdots, \tag{7}$$

$$T_{\text{Coop-eve,i,e2e}} = (3T_{\text{pro}} + 2T_{\text{tra}})\frac{N_{\text{reTra}}}{2} + 2T_{\text{pro}} + T_{\text{tra}} \quad N_{\text{reTra}} = 0, 2, 4, \cdots, \tag{8}$$

$$T_{\text{DCC-odd,i,e2e}} = (3T_{\text{pro}} + T_{\text{tra}} + T_{\text{dyna}})\frac{N_{\text{reTra}}+1}{2} \quad N_{\text{reTra}} = 1, 3, 5, \cdots, \tag{9}$$

$$T_{\text{DCC-eve,i,e2e}} = (3T_{\text{pro}} + T_{\text{tra}} + T_{\text{dyna}})\frac{N_{\text{reTra}}}{2} + 2T_{\text{pro}} + T_{\text{tra}} \quad N_{\text{reTra}} = 0, 2, 4, \cdots, \tag{10}$$

where T_{dyna} is the dynamic transmission time for the cooperative node retransmitting to the receiver when starting ARQ mechanism in the DCC-ARQ protocol, and can be expressed as

$$T_{\text{dyna}} = N_{\text{li}} T_{\text{bl}}, \tag{11}$$

which is dynamic and determined by the the channel link quality between the transmitter node and the cooperative node. Hence the start time for the cooperative node to send the redundancy blocks is dynamic, which is so-called dynamic coded cooperation.

For one specific case, if $N_{\text{reTra}} = 1$, it is the first "full cycle" as shown in Fig. 4.

III. Numerical Results

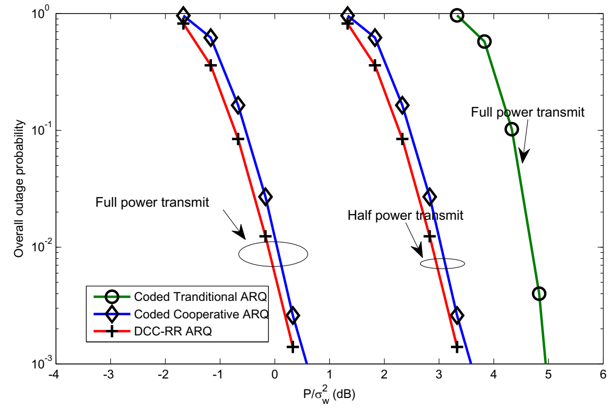
A. Simulation Setup

We consider a multi-hop UWA network with $N_{\text{h}} = 5$ hops, and the distance between each hop is $d = 2$ km. Assuming that there is only one cooperative node, and it lies in the middle of the hop. In each burst, there are $N_{\text{bl}} = 20$ blocks which are erasure-correction coded over $I_{\text{bl}} = 10$ information blocks, i.e., 0.5 bit/symbol. The OFDM parameters are chosen as in [17], with the number of OFDM subcarrier $K = 1024$. The system center frequency is $f_c = 10$ kHz. The multipath channels are randomly generated with 50 taps in the baseband, and are assumed as quasi-static fading.

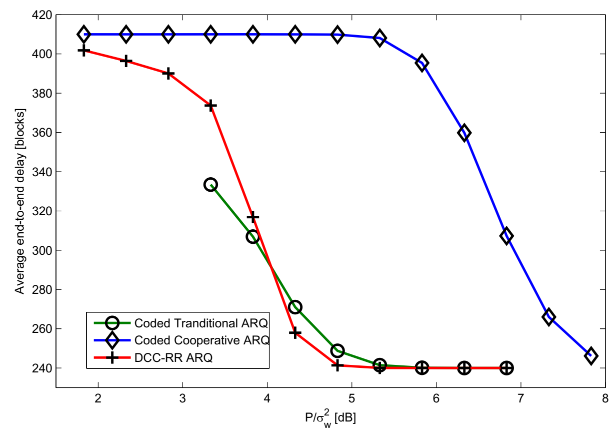
During the relay process, we claim one node successfully recovering the transmitted message when its cumulative mutual information of received blocks is no less than the amount of transmitted information bits. In contrast, outage occurs that when one node finishes transmission, its downstream node can recover the relayed message.

The received signal-to-noise ratio (SNR) of an UWA system can be expressed by the passive sonar equation:

$$\text{SNR} = \text{SL} - \text{TL} - \text{NL} + \text{DI}, \tag{12}$$



(a) Overall outage probability



(b) Average end-to-end delay

Fig. 5. Performance comparison of several ARQ protocols for 5-hop UWA networks. There is only one cooperative node in each hop. The maximize retransmission time is only once in each hop. Code rate is 0.5.

where SL is the source power level, TL is the transmission loss, NL is the noise power level, and DI is the receiving directivity index in decibels. We consider the receivers as non-directional hydrophones, and thus the receiving directivity index is zero.

Define $\sigma_d^2(f)$ as the attenuation of the signal at frequency f after transmitting a distance d,

$$\sigma_d^2(f) := d^\beta \alpha(f)^d, \tag{13}$$

where $\alpha(f)$ is the frequency-dependent absorption coefficient, and β is the path-loss exponent which is taken as 1.5 in a practical system. Then the transmission loss TL can be expressed as

$$\begin{aligned} \text{TL} &= 10 \log \sigma_d^2(f) \\ &= \beta \cdot 10 \log(d) + d \cdot 10 \log \alpha(f). \end{aligned} \tag{14}$$

The ambient noise in the ocean can be modeled using turbulence,shipping,waves and thermal noise. The overall power spectral density on the ambient noise is given by [18]

$$\begin{aligned} \text{NL} &= 10 \log N(f) \\ &= 10 \log[N_t(f) + N_s(f) + N_w(f) + N_{th}(f)]. \end{aligned} \tag{15}$$

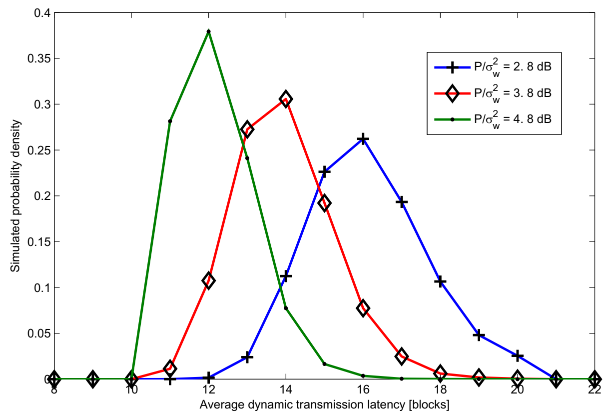


Fig. 6. Simulated distribution of average dynamic transmission latency for each hop for the proposed DCC-RR ARQ protocol.

Define the transmission SNR as the transmission power over the ambient noise variance, i.e.,$\bar{\gamma} := P/\sigma_w^2$, which can be obtained from $10 \log \bar{\gamma} = \mathrm{SL} - \mathrm{NL}$.

For simplicity, we set the maximize retransmission times is only once during the simulation, i.e.,$N_{\mathrm{reTra}} = \{0, 1\}$. To compare with the proposed DCC-ARQ protocol, both traditional ARQ and cooperative ARQ protocols are equipped with erasure-correction channel code, and the code rate is 0.5. Further, as our early work [14] indicated, RR cooperation is more convenient than ER for DCC in UWA system, we adopt DCC-RR ARQ scheme for simulation in this paper.

B. Simulation Results

For the system operating at one frequency point, Fig. 5(a) demonstrates the simulated outage probabilities of the three different protocols. One can see that the proposed DCC-ARQ scheme is slightly better than the coded cooperative ARQ scheme in [4], and both of them outperform the coded traditional ARQ scheme.

Average over channel dynamics, Fig. 5(b) shows the end-to-end delay of the three ARQ schemes. We can find that the proposed DCC-ARQ method outperforms the coded cooperative ARQ scheme via the transmission latency adaptation, while it is close to the coded traditional ARQ scheme. Hence, the proposed DCC-ARQ protocol achieves good balance between the reduced end-to-end delay and decent outage performance, relative to existing protocols.

Fig. 6 demonstrates the simulated probability density function of the average dynamic transmission latency in the proposed scheme. Compared with the coded cooperative ARQ scheme, a lower transmission latency T_{dyna} in the proposed DCC-ARQ scheme leads to a reduced end-to-end delay.

IV. Conclusions

In this paper, we investigated a dynamic coded cooperative ARQ scheme for a multi-hop UWA network. Compared with the traditional ARQ and the cooperative ARQ protocols numerical results showed that the proposed protocol can achieve good balance between the reduced end-to-end delay and decent outage performance through dynamic cooperation.

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References

[1] X. Xu, Z.-H. Wang, S. Zhou, and L. Wan, “Parameterizing both path amplitude and delay variations of underwater acoustic channels for block decoding of orthogonal frequency division multiplexing,” *The Journal of the Acoustical Society of America*, vol. 131, no. 6, pp. 4672–4679, Jun. 2012.

[2] X. Xu, S. Zhou, A. K. Morozov, and J. C. Preisig, “Per-survivor processing for underwater acoustic communications with direct-sequence spread spectrum,” *The Journal of the Acoustical Society of America*, vol. 133, no. 5, pp. 2746–2754, May 2013.

[3] S. Azad, P. Casari, F. Guerra, and M. Zorzi, “On ARQ strategies over random access protocols in underwater acoustic networks,” in *Proceedings of MTS/IEEE Oceans Conference*, Spain, June 6-9 2011.

[4] J.-W. Lee and H.-S. Cho, “A cooperative ARQ scheme for multi-hop underwater acoustic sensor networks,” in *Proceedings of IEEE Symposium on Underwater Technology (UT) and 2011 Workshop on Scientific Use of Submarine Cables and Related Technologies (SSC)*, Tokyo, April 5-8 2011.

[5] H. Mo, A.-C. Mingir, H. Alhumyani, Y. Albayram, and J.-H. Cui, “UW-HARQ: An underwater hybrid ARQ scheme: Design, implementation and initial test,” in *Proceedings of MTS/IEEE Oceans Conference*, Hampton Roads, VA, Otc 14-19 2012.

[6] Y. Chen, H. Sun, L. Wan, Z.-H. Wang, S. Zhou, and X. Xu, “Dynamic network coded cooperative OFDM for underwater data collection,” in *Proceedings of MTS/IEEE Oceans Conference*, Hampton Roads, VA, Otc14-19 2012.

[7] S. Azad, P. Casari, and M. Zorzi, “The underwater selective repeat error control protocol for multiuser acoustic networks: Design and parameter optimization,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 10, pp. 4866–4877, 2013.

[8] G. Al-Habian, A. Ghrayeb, M. Hasna, and A. Abu-Dayya, “Threshold-based relaying in coded cooperative networks,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 123–135, Jan. 2011.

[9] Q. Li, S. Ting, and C.-K. Ho, “A joint network and channel coding strategy for wireless decode-and-forward relay networks,” *IEEE Trans. Commun.*, vol. 59, no. 1, pp. 181–193, Jan. 2011.

[10] T. Hunter and A. Nosratinia, “Diversity through coded cooperation,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 283–289, Feb. 2006.

[11] J. Castura and Y. Mao, “Rateless coding for wireless relay channels,” *IEEE Trans. Veh. Technol.*, vol. 6, no. 5, pp. 1638–642, May 2007.

[12] K. Kumar and G. Caire, “Coding and decoding for the dynamic decode and foward relay protocol,” *IEEE Trans. Inform. Theory*, vol. 55, no. 7, pp. 3186–3205, Jul. 2009.

[13] K. Ishibashi, K. Ishii, and H. Ochiai, “Dynamic coded cooperation using multiple Turbo codes in wireless relay networks,” *IEEE J. Select. Topics Signal Proc.*, vol. 5, no. 1, pp. 197–207, Feb. 2011.

[14] Y. Chen, Z.-H. Wang, L. Wan, H. Zhou, S. Zhou, and X. Xu, “OFDM modulated dynamic coded cooperation in underwater acoustic channels,” *IEEE Journal of Oceanic Engineering, doi: 10.1109/JOE.2014.2304254*, 2014.

[15] K. Ishibashi, K. Ishii, and H. Ochiai, “Design of adaptive coded cooperation using rate compatible turbo codes,” in *Proceedings of the 70th IEEE Vehicular Technology Conference Fall*, Anchorage, AK, Sep. 20-23 2009.

[16] Z.-H. Wang, S. Zhou, Z. Wang, B. Wang, and P. Willett, “Dynamic block-cycling over a linear network in underwater acoustic channels,” in *Proceedings of WUWNET’12*, Los Angeles, CA, USA, Nov. 5-6 2012.

[17] H. Yan, L. Wan, S. Zhou, Z. Shi, J.-H. Cui, J. Huang, and H. Zhou, “DSP based receiver implementation for OFDM acoustic modems,” *Elsevier Physical Communication*, vol. 5, no. 1, pp. 22–32, Mar. 2012.

[18] M. Stojanovic, “On the relationship between capacity and distance in an underwater acoustic communication channel,” in *Proc. First ACM International Workshop on Underwater Networks / MobiCom Conference*, Los Angeles, CA, Sep. 2006.