

Dynamic Node Cooperation in an Underwater Data Collection Network

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Abstract—In this paper, we consider a practical underwater data collection network, where one destination needs to collect data from multiple underwater nodes. With the conventional automatic-repeat-request (ARQ) protocol, the destination requests retransmission from each node individually without any node cooperation. We propose two protocols, selective relay cooperation and dynamic network coded cooperation, utilizing the fact that underwater nodes can overhear the transmission of the others. In the selective relay cooperation, one node can be selected as a relay to transmit the data from another undecoded node in the retransmission phase. In the network coded cooperation, the selected relay nodes transmit network coded packets to the destination. The relay nodes participating the cooperation are selected by the destination based on the channel quality, as measured by the effective signal-to-noise ratio. In addition to simulation results, we have carried out several lake tests based on a full protocol implementation. Simulation and field testing results demonstrate that the proposed schemes can gain significant performance improvement compared with the conventional ARQ scheme.

Index Terms—ARQ, data collection, dynamic network coded cooperation, selective relay cooperation, underwater acoustic network.

I. INTRODUCTION

UNDERWATER acoustic (UWA) communication systems and networks have attracted much attention, due to its potential in various applications including scientific research,

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commercial development and military defense [2]–[4]. In recent years, significant progress has been made both on physical-layer transceiver and upper-layer protocol designs [5]–[7]. A significant shift of focus is towards testbed development and practical applications. Various testbeds are under development by different groups, see [8]–[13].

A. Scope and Contributions of This Paper

This paper focuses on one practical application of environmental monitoring, where multiple distributed sensors monitor phenomena in underwater environments, and the sensor data need to be collected and disseminated timely to potential users [14]. As an example, in [15], a bottom modem transmits sensory data from underwater instruments to surface with information on weather, water condition and water quality, where the underwater data is updated on the internet hourly. This paper considers an extended scenario, where one surface buoy collects data from multiple nodes.

By using acoustic waves to carry information, the UWA communications can accomplish wireless data harvesting while avoid installation and maintenance costs associated with wired cable. On the other hand, UWA communications suffer from temporarily and spatially varying packet loss due to the severe fading of UWA channels. When errors happen, the traditional ARQ approach is to ask the nodes to resend. Note that however, nodes can overhear the transmissions from other nodes, and nodes having good channels to the destination could help the nodes with poor connections to the destination. How to harness the benefits of node collaboration without complicating the system design is the focus of this paper for a practical data collection network.

Specifically, the contributions of this paper are as follows.

- We propose two approaches based on dynamic node cooperation, selective relay cooperation (SRC) and dynamic network coded cooperation (DNC) protocols. In the selective relay cooperation, instead of retransmission by the undecoded node itself, another node who has overheard the transmission successfully and has a better channel condition will be selected as a relay. In the network coded cooperation, each selected relay node transmits a network coded packet combining the overheard data from several undecoded nodes. The cooperation schedules are optimized at each transmission round by the central control node based on the collected information, especially the channel quality as reported by the physical layer.

- In addition to simulation results, we implement the ARQ, SRC, and DNC protocols on real systems, and carry out three lake tests, which demonstrate the effectiveness of the proposed strategies based on online data decoding results. This effort is well aligned with the current emphasis of field testings of underwater communication and networking solutions.

Note that the considered network is a one-hop small-scale network with one central coordinator. Issues regarding to a large-scale network are beyond the scope of this paper.

B. Related Work

This paper focuses on a particular data collection network and proposes dynamic node cooperation solutions for improved performance. In the literature, various schemes have been explored with different setups to improve the transmission reliability.

- *Relay*: Cooperative communication or relay-aided communication can cope with packets loss significantly, as explored in [16]–[22].
- *Erasur Coding*: Erasure correction coding across multiple packets at the data link layer provides a means of reliable communication against channel disruptions, as shown in [23] and [24].
- *Network Coding*: At the network layer, an intermediate node can generate packets by combing packets from different nodes to improve the end-to-end reliability [25]–[28].
- *ARQ*: Retransmission mechanisms such as ARQ and its derivatives have been studied in [29]–[31], and combined with other methods such as network coding in [32].

All these references have a different network topology from the one considered in this paper.

The setup in this paper is mostly related to the setup in [33] and [34], where adaptive network coded cooperation (ANCC) and the generalized adaptive network coded cooperation (GANCC) are pursued for a wireless sensor network. The ANCC and GANCC are appealing for data collection networks where the coding structure matches well with the underlying network topology. The main differences between our work and those in [33] and [34] are as follows. 1) The cooperation schedule in [33] and [34] is pre-determined with one broadcasting phase and one cooperation phase where all the nodes participate. 2) A homogeneous network, where all the communication channels have similar signal to noise ratios (SNR), is assumed in [33] and [34]. We consider a heterogeneous network where the different link quality plays an important role. 3) The focus in [33] and [34] is on the code design and the receiver signal processing while here we focus on the complete protocol implementation and real-time field validation.

The rest of this paper is organized as follows. Section II presents the considered system model. Section III describes the proposed selective relay cooperation and dynamic network coded cooperation protocols in details, respectively. Section IV contains simulation results for one assumed topology, and Section V shows the numerical performance results in lake

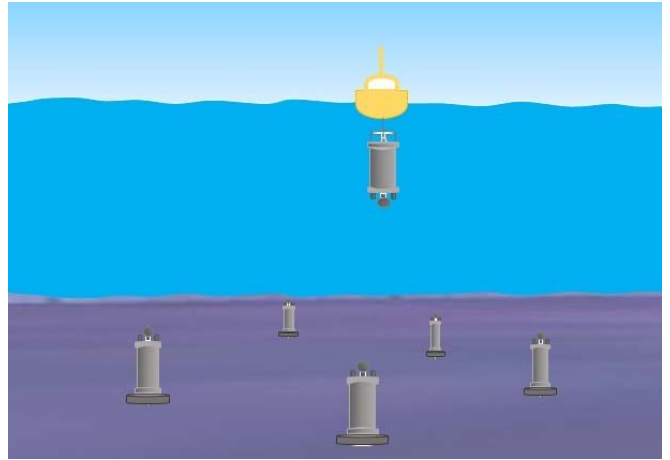


Fig. 1. An example network with one surface buoy to collect data from multiple underwater nodes periodically.

tests with several network settings. Finally, conclusions are drawn in Section VI.

II. SYSTEM SETUP

Fig. 1 depicts an example underwater network, where one surface buoy needs to collect data from multiple bottom nodes through acoustic links. Assume that there are N_u bottom sensor nodes. Each node samples environmental parameters on its own schedule. The surface buoy will collect the data from the bottom nodes periodically, and then publish the data to a data center through a wireless radio link.

The surface buoy is often solar powered and all the attached units can be always on. The acoustic modems on the bottom nodes are in a sleep mode until being triggered. The distances of the sensor nodes to the destination are known to the surface node during the deployment or measured through the ranging function of the modems.

A conventional stop-and-wait ARQ protocol can be designed as follows.

- The surface node initiates one data collection cycle by sending out a request to receive (RTR) message. This message specifies the waiting time T_i before node i can send out its data to the destination. This sets up the transmission order, and can avoid the possible collisions among the replies with enough guard time between consecutive transmissions.
- All the N_u nodes send back their data packets subject to the transmission order. The surface node decodes all the incoming messages.
- If the surface node has not collected all the N_u packets correctly, it sends out a negative acknowledgement (NACK) message, requesting only those nodes with missing data to resend their packets subject to a given order.
- After all the messages are correctly received, or when the maximum number of rounds of transmission is reached, the surface node can send out an acknowledgement (ACK) message to terminate the current collection cycle. Upon receiving the ACK, all the bottom nodes go back to the sleep mode.

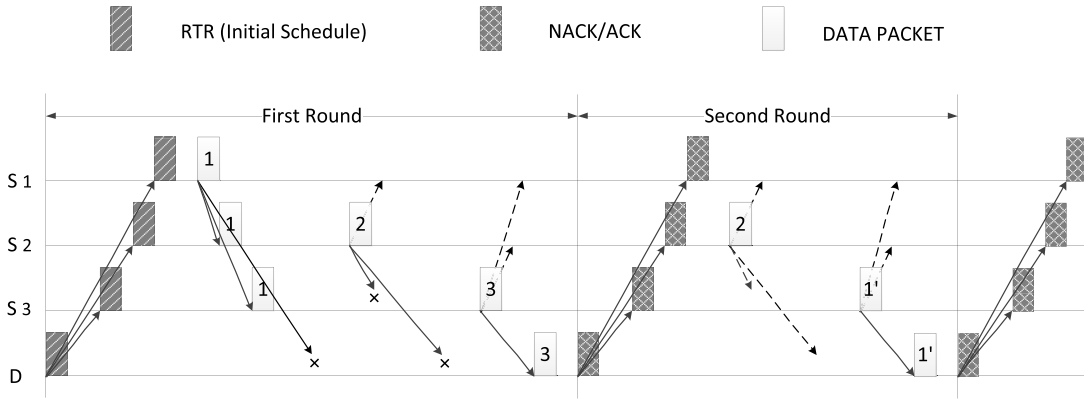


Fig. 2. Illustration of the SRC protocol with $N_u = 3$ nodes. In the first round, the packets from node 1 and node 2 were not received. In the second round, node 2 repeats its transmission while node 3 relays the packet from node 1.

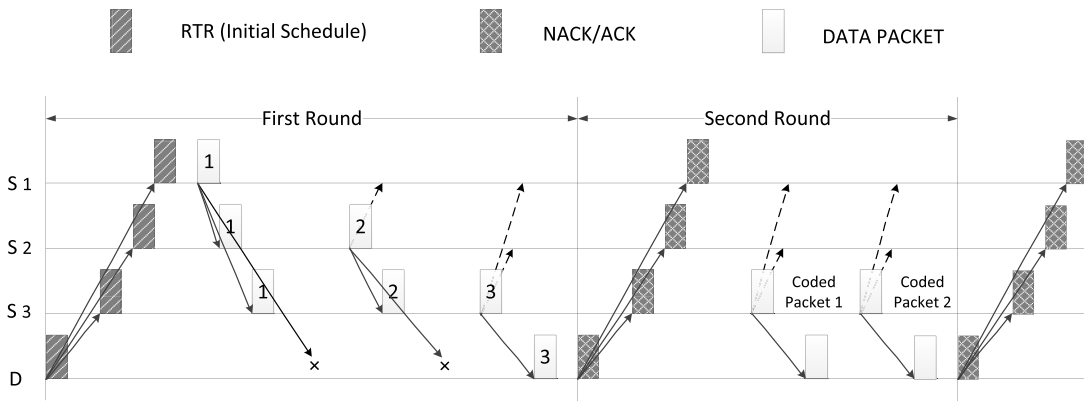


Fig. 3. Illustration of the DNC protocol with $N_u = 3$ nodes. In the first round, the packets from node 1 and node 2 were not received. In the second round, node 2 and node 3 send out a network coded packet based on the packets overheard from node 1 and node 2.

The conventional ARQ protocol does not rely on the collaboration among the sensor nodes. Although each node can overhear the transmission from the preceding transmissions, however, it simply discards its received messages. In the next section, we will describe two protocols that rely on dynamic node cooperation to improve the efficiency of the data collection procedure.

III. DYNAMIC NODE COOPERATION BASED PROTOCOLS

Due to the broadcast nature, one node's transmission to the destination can be overheard by other nodes. Hence, one node can serve as a relay to another node, to potentially improve the system efficiency. We present two different protocols, selective relay cooperation as illustrated in Fig. 2, and dynamic network coded cooperation as illustrated in Fig. 3. Both protocols share the same processing in the initial round.

A. Initial Round

The destination sends RTR to announce a schedule which indicates the order of transmission for N_u nodes. When one node transmits its data to the destination, all other nodes are in the listening mode, and can overhear the transmission. Depending on the channel conditions, one node might not be able to decode all the overheard messages successfully.

Each packet consists of a packet header and the data payload. When node i transmits, it reports in the header whether it has decoded the data from other nodes. The destination decodes the received data from N_u nodes sequentially. At the end of this round, the destination has the following information at hand.

- The data packets from the nodes whose transmission was successfully received, and the set \mathcal{S} of nodes whose transmission was not correctly received.
- The link quality from each node to the destination, in the form of effective signal to noise ratio (ESNR).

$$[\text{ESNR}_1, \dots, \text{ESNR}_{N_u}]. \quad (1)$$

This ESNR is provided by the modem physical layer, e.g., defined in [39] for the orthogonal-frequency-division-multiplexing (OFDM) transmission. The ESNR_i is set to zero if the decoding from the i th node is unsuccessful.

- An $N_u \times N_u$ matrix

$$\begin{bmatrix} I_{1,1} & \cdots & I_{1,N_u} \\ \vdots & \ddots & \vdots \\ I_{N_u,1} & \cdots & I_{N_u,N_u} \end{bmatrix},$$

where the entry $\{I_{j,i}\}$ is set to be one if the data packet from node i is available at node j , and zero otherwise.

Note that only partial information is available at this round due to the transmission order. The node which transmitted at the earlier time slot can overhear and decode the packets from later nodes, but can not feed back relevant information to the destination until the next round.

If all the data from N_u nodes are decoded correctly in this initial round, the destination sends out an ACK signal to terminate the data collection procedure. Otherwise, it will proceed to the next step trying to recover the missing packets, as described in Section III-B or Section III-C.

B. Selective Relay Cooperation

Suppose that there are P nodes whose decoding was not successful in the first round. The destination will request a retransmission of the data packets from P nodes. Different from the conventional ARQ protocol, the P nodes in the retransmission phase could be different from those undecoded nodes. Due to the overhearing, the packets from those undecoded nodes are now available at other nodes, and hence their data could be relayed to the destination. The key issue is to determine an updated transmission schedule according to the collected information.

We denote the set of undecoded nodes as \mathcal{S} with P entries. Suppose that node i will be relayed by another node indexed as $\pi(i)$, the set of relays is denoted as

$$\mathcal{R} = \{\pi(i)\}, \quad i \in \mathcal{S}. \quad (2)$$

To optimize the performance, the proposed schedule is

$$\mathcal{R}^* = \arg \max_{\mathcal{R}} \left(\prod_{i \in \mathcal{S}} I_{\pi(i),i} \right) \cdot \left(\sum_{i \in \mathcal{S}} \text{ESNR}_{\pi(i)} \right). \quad (3)$$

The relays in \mathcal{R} can be distinct, i.e., $\pi(i_1) \neq \pi(i_2)$ when $i_1 \neq i_2$, or one node can be used multiple times. This is a decision to be considered by the system before carrying out the optimization problem in (3). From the system point of view, the relays with lower ESNRs will transmit earlier within the relay set \mathcal{R} . As the relays with lower ESNRs have higher outage probability, the relay with a higher ESNR which transmits at a later time slot has more chance to send the data and side information to the destination successfully and has more potential to be a relay in the next round.

The destination announces the updated schedule to the underwater nodes. The selected relay nodes transmit the specified packets to the destination. Other nodes are in the listening mode, and update their own local information $I_{j,i}$ based on the received new packets. The destination decodes the received blocks, either based on the signals from the second round alone, or combining the signals from the first and second rounds.

If all the P nodes are decoded, the destination sends out an ACK to terminate the procedure. Otherwise, another round could be initiated. The processing at further rounds are similar to the second round, except that the collected information is updated. There exists a possibility that not all the packets can be collected even after several rounds. After a pre-specified maximum number of rounds, the destination can abort the data collection process by issuing an ACK message, and labels the

data of the current time period as ‘‘missing’’. After getting the ACK message or a timeout, all the underwater nodes discard the collected data from other nodes and go to the sleep mode.

C. Dynamic Network Coded Cooperation

There are P nodes in the set \mathcal{S} that have not been correctly received. The destination now selects Q nodes in the second round for retransmission. Let \mathbf{c}_i denote the channel codeword for node i that is encoded in a finite field. Assume that a relay set \mathcal{R} is selected, and the j -th relay will send

$$\tilde{\mathbf{c}}_j = \alpha_{j,i_1} I_{j,i_1} \mathbf{c}_{i_1} \oplus \alpha_{j,i_2} I_{j,i_2} \mathbf{c}_{i_2} \oplus \cdots \oplus \alpha_{j,i_P} I_{j,i_P} \mathbf{c}_{i_P}. \quad (4)$$

where $i_1, \dots, i_P \in \mathcal{S}$ and $\{\alpha_{j,i_1}, \dots, \alpha_{j,i_P}\}$ are the coefficients in a finite field. The relationship on the finite field can be represented by the following matrix-vector representation:

$$\begin{bmatrix} \tilde{\mathbf{c}}_{j_1} \\ \vdots \\ \tilde{\mathbf{c}}_{j_Q} \end{bmatrix} = \begin{bmatrix} \alpha_{j_1,i_1} I_{j_1,i_1} & \cdots & \alpha_{j_1,i_P} I_{j_1,i_P} \\ \vdots & \ddots & \vdots \\ \alpha_{j_Q,i_1} I_{j_Q,i_1} & \cdots & \alpha_{j_Q,i_P} I_{j_Q,i_P} \end{bmatrix} \begin{bmatrix} \mathbf{c}_{i_1} \\ \vdots \\ \mathbf{c}_{i_P} \end{bmatrix}. \quad (5)$$

To improve the system performance, the relay selection is decided by the measured ESNRs as:

$$\mathcal{R}^* = \arg \max_{\mathcal{R}} f(\mathcal{R}, \mathcal{S}) \cdot \left(\sum_{j \in \mathcal{R}} \text{ESNR}_j \right), \quad (6)$$

where $f(\mathcal{R}, \mathcal{S})$ specifies whether the relay set \mathcal{R} is a valid relay set for \mathcal{S} . If $Q \leq P$, all the rows in the $Q \times P$ mixing matrix in (5) shall be linearly independent. If $Q > P$, any P rows from the mixing matrix shall be linearly independent.

If the destination correctly decodes more than P network coded packets, then a hard decoding through matrix inversion on the finite field can be used to recover the P missing data packets. If not, iterative channel and network decoding as in [35] can be applied at the physical layer to decode all the missing packets from the nodes in \mathcal{S} simultaneously; (note that an extension along this line has been carried out in [36].) The choice of Q is decided by the destination based on the its receiving capability. Choosing a Q larger than P would improve the probability of success in the second round, and allows the use of the hard decoding algorithm, at the expense of $Q - P$ extra transmission as compared with the SRC protocol. Choosing a Q less than P means that the joint channel and network decoding algorithm has to be used to reduce the number of packet retransmissions. The DNC protocol offers such a design flexibility as compared to the relay operation. In this paper, however, we choose $Q = P$ when comparing DNC and SRC protocols.

If the second round is not successful, further rounds of transmission can be requested in a similar fashion. Note that the overhearing nodes need to update $\{I_{j,i}\}$ based on its stored data together with newly received network coded packets.

IV. SIMULATION RESULTS

We assume one specific geographical topology as shown in Fig. 4 to conduct simulations, where there are $N_u = 5$ underwater sensor nodes and one destination. The relative distances are marked in Fig. 4.

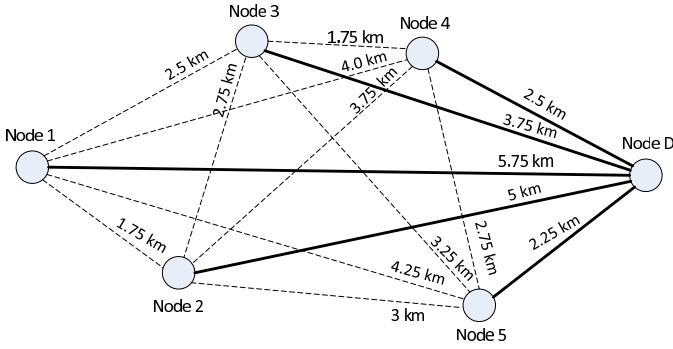


Fig. 4. The network topology used in simulation.

Although the protocols are compatible with other modulation schemes, we use the OFDM modulation in simulation. The OFDM parameters are chosen as in [37], with the number of OFDM subcarrier $K = 1024$. The multipath channels are randomly generated with 50 taps in the baseband, and are assumed as quasi-static fading. At the k th subcarrier, the channel input-output relationship for node i is:

$$z_i[k] = H_i[k]s_i[k] + w_i[k], \quad (7)$$

where $H_i[k]$ is the channel frequency response on the k th subcarrier, and $w_i[k]$ is the additive noise. We use E_s to denote the symbol energy and N_0 the noise variance on each OFDM subcarrier. Perfect channel knowledge is available at the receiver. The effective ESNR is the average SNR at the receiver side,

$$\text{ESNR}_i = \frac{1}{K} \sum_k |H_i[k]|^2 \cdot E_s / N_0. \quad (8)$$

Note that the average SNR is distance-dependent, and we assume that a spreading factor of 1.5, and the SNR decreases as proportional to $d^{-1.5}$ where d is the propagation distance. The average energy of the channel from node 5 to the destination $E[|H_5[k]|^2]$ is normalized to be 1, and the other channels can be computed accordingly.

Instead of a practical code, here we assume capacity-achieving codes and use the mutual information to evaluate the outage probabilities of whether a packet can be decoded correctly at the receiver. For simplicity, we assume that the decoding in each round is determined by the received signals in this round only, not combined with the signals from the previous rounds. An outage occurs if the total mutual information at the destination is lower than the information rate r , which is as

$$p_i = \Pr \left\{ \frac{1}{K} \sum_{k=-K/2}^{K/2-1} \log_2 \left(1 + |H_i[k]|^2 \frac{E_s}{N_0} \right) < r \right\}. \quad (9)$$

For network coded transmission with $Q = P$, a joint decoding across all the P received blocks are assumed with an outage probability

$$\tilde{p} = \Pr \left\{ \frac{1}{K} \sum_{j \in \mathcal{R}} \sum_{k=-K/2}^{K/2-1} \log_2 \left(1 + |H_j[k]|^2 \frac{E_s}{N_0} \right) < Pr \right\}. \quad (10)$$

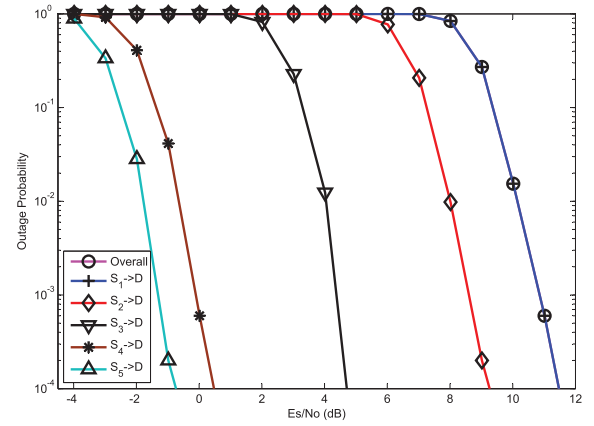


Fig. 5. Outage probability for the underwater nodes without cooperation.

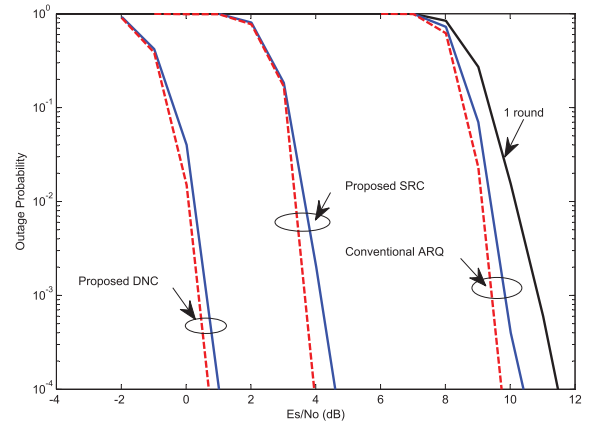


Fig. 6. The overall system outage probability for the three schemes. Dash lines: a maximum of 3 rounds; Solid lines: a maximum of 2 rounds.

In the first round, the destination schedules node 1 to transmit at first, and node 5 to transmit at last, according to their distances to the destination. The closer node has lower spreading loss, less outage probability and higher chance to be a relay.

We set the information rate as 0.5 bit per OFDM subcarrier. Fig. 5 depicts the outage probabilities for 5 underwater nodes to the destination without any cooperation. The performance of node 1 limits the overall system's performance seriously.

As a figure of merit, we evaluate the overall system performance concerning all the 5 nodes. Only when the destination collects the data from all the nodes correctly, the data collection procedure is regarded as successful, otherwise an outage is declared. In each round, we limit that each node in the relay set can be used only once. Fig. 6 shows the probability of the system outage, where the proposed SRC scheme has about 6 dB gain compared with the conventional ARQ, and the proposed DNC scheme has more than 9 dB gain. For the ARQ or SRC scheme, using three rounds leads to additional 0.8 dB gain compared with using two rounds.

With the SRC scheme as an example, Fig. 7 plots the probability distribution of the number of relays adopted dynamically in the second round. For this particular geometry, only two or three relays are adopted in general.

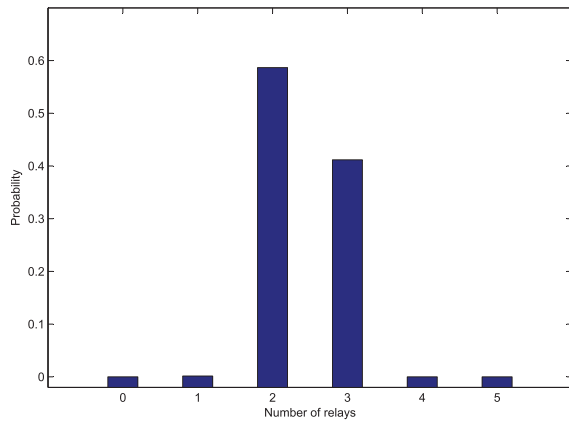


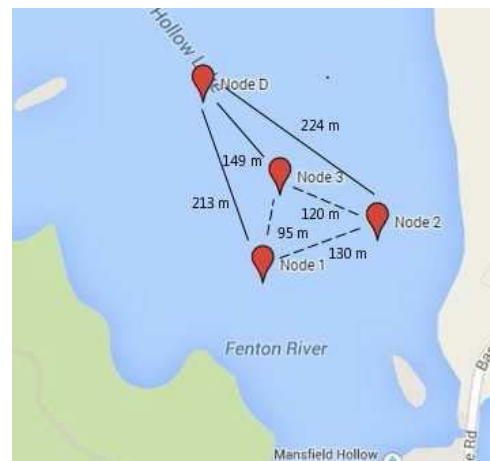
Fig. 7. The probability distribution of the number of relays adopted in the second round for SRC. SNR varies from 1 to 5 dB.

V. LAKE TESTING RESULTS

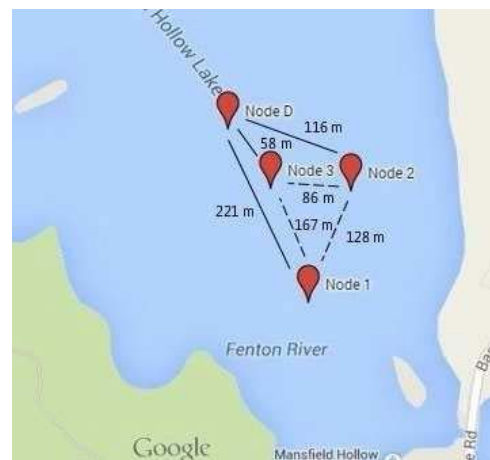
Three field tests were taken in the Mansfield Hollow lake, Connecticut on Oct. 29, Nov. 11, and Nov. 25, 2014, respectively. The network topologies are shown in Fig. 8, where there are one destination node and three sensor nodes. The pairwise distances among all the nodes are marked, which were obtained using the ranging function of the acoustic modems. The average depth of the lake was about 4 to 5 meters.

Each node consists of a surface buoy and an OFDM modem. Electronics, including gumstix, the power module, and the wireless module, are housed inside the buoy. Outside the buoy, there are a global-positioning-system (GPS) unit, a wireless antenna and a connector to the OFDM modem. The illustration of each node is shown in Fig. 9, where the OFDM modem is deployed at a water depth about 1 meter. In the tests, one laptop with a wireless module is used to send out messages to the control platform in one buoy to trigger the data collection cycle. An example channel impulse response is shown in Fig. 10, where the lake is shallow with a muddy bottom full of sea weeds. The delay spread is very large, more than 100 ms, due to the reverberation effect.

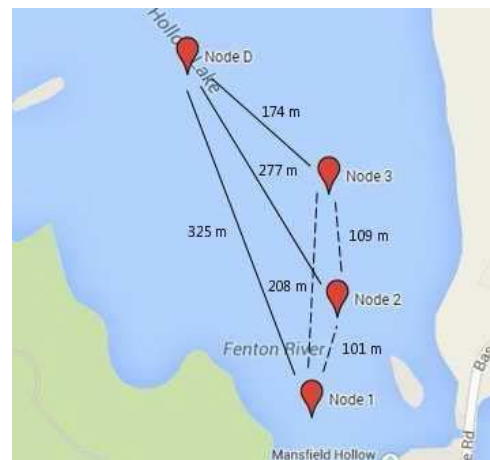
Three protocols have been tested: ARQ, SRC, and DNC. The maximum transmission power of the OFDM modems at 0dB is 20W, and the power level can be changed by the user. In the lake tests, the power level of RTR and NACK/ACK was set to be -20 dB to guarantee the command message transmission. The power of the data transmission was set to a lower level. Each data packet consisted of one synchronization preamble of duration about 0.5 second, and one OFDM block of duration 0.17 second [38], [39]. The time slot is set to be 10s for time division access. The RTR message includes Node ID, Packet Number, and Allocation Schedule. DATA packet includes Node ID, Packet Number, Power Level, Overhearing Status $I_{j,i}$, and payload data. ACK/NACK message includes Node ID, Packet Number, and ACK announcement. Due to the deployment challenges, for each protocol we have collected 25 data bursts on Oct. 29 in two power levels, 25 data bursts on Nov. 11 in one power level, and 30 data bursts on Nov. 25 in one power level respectively.



(a)



(b)

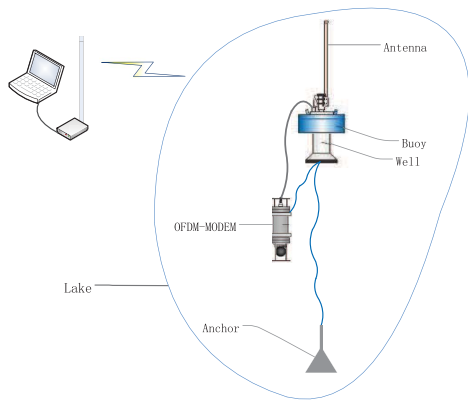


(c)

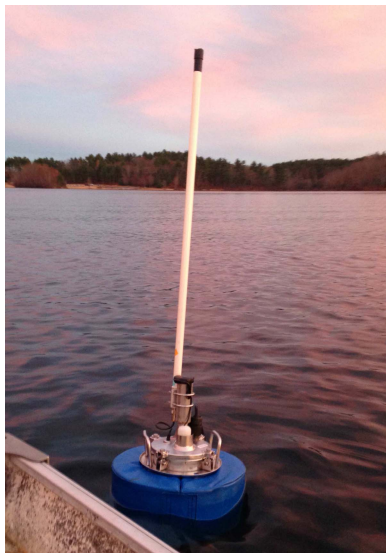
Fig. 8. The topologies for the three lake tests, where all the distances are marked. (a) Oct. 29, 2014. (b) Nov. 11, 2014. (c) Nov. 25, 2014.

Figs. 11-14 present the performance of the three protocols by the numbers of successful transmitted packets to the destination at each transmission round and final numbers of successful data collection bursts for the three lake tests. We have the following observations.

- For ARQ, the retransmission from the node with an unsuccessful transmission does not improve the total number of received packets. This could be due to channel



(a)



(b)

Fig. 9. The communication node used in the lake tests. (a) Illustration. (b) In deployment.

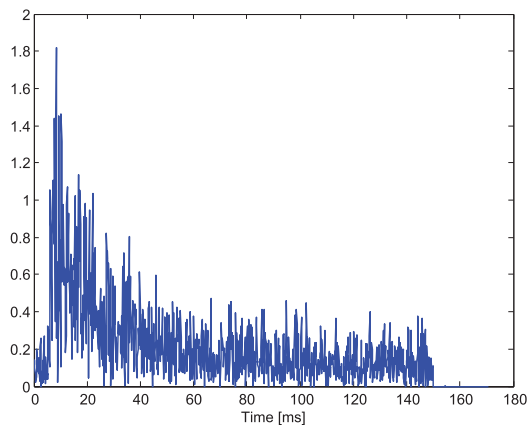


Fig. 10. Example channel impulse response.

temporal correlations, as two close transmissions from one node suffer from the same channel conditions.

- In the first two lake tests at different power levels and locations, there was always one node failed at the first round, sometimes node 1 and sometimes node 2. Hence, the DNC is equivalent to the SRC, and just one relay helped to relay the overheard message.

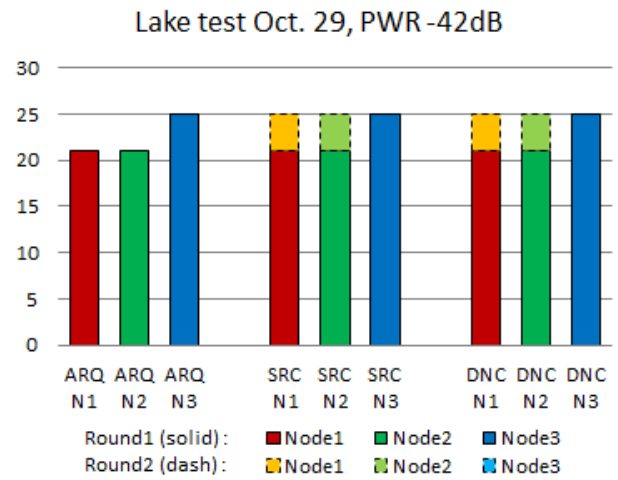


Fig. 11. The numbers of collected packets from different nodes; Lake test Oct. 29, 2014, power level -42 dB.

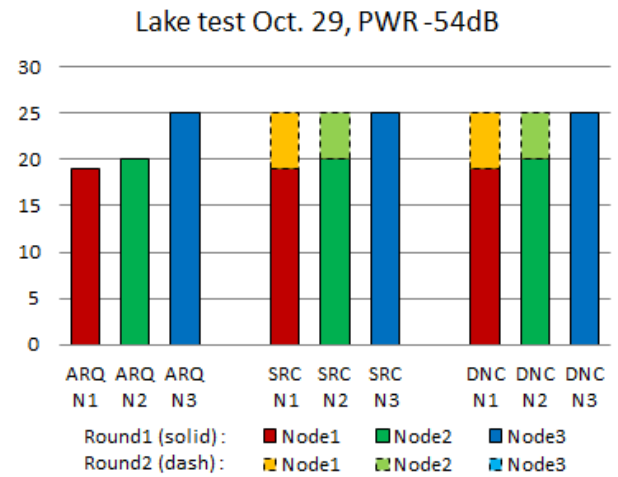


Fig. 12. The numbers of collected packets from different nodes; Lake test Oct. 29, 2014, power level -54 dB.

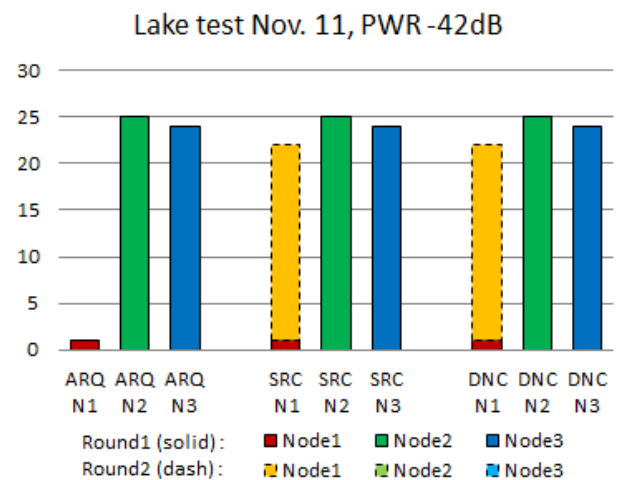


Fig. 13. The numbers of collected packets from different nodes; Lake test Nov. 11, 2014, power level -42 dB.

Nonetheless, Figs. 11-13 show that the relay operation considerably improve the packet delivery rate than ARQ.

- In the third lake test on Nov. 25, the distances between nodes were larger compared to the previous two tests.

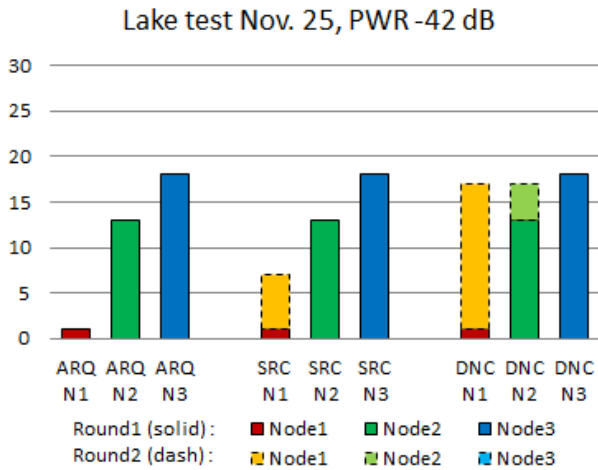


Fig. 14. The numbers of collected packets from different nodes; Lake test Nov. 25, 2014, power level -42 dB.

From Fig. 14, SRC outperforms ARQ and DNC outperforms SRC. For SRC, with 2 times node 2 forwarded data from node 1, 3 times node 3 forwarded from node 1, and 2 times node 2 forwarded data from node 1 plus node 3 retransmit itself successfully. Hence, there are 7 more successful data bursts in SRC. For DNC with real implementation, we allowed one node to be used multiple times to show distinctions with SRC. In addition to the one-node relay operations as in the SRC protocol, there were 10 times that node 3 forwarded the network coded packet for node 2 and node 1. In total there are 17 more successful data bursts in the DNC operation compared to the ARQ operation.

Note that a direct comparison between simulation results and lake test results is not feasible, because 1) the system setup and channel conditions are different; and 2) theoretical outage probability and perfect channel knowledge are used in the simulation while practical modems are used in lake tests. In addition, lake test data sets are very limited. Nevertheless, lake test results validate that SRC and DNC can improve the data collection performance when there are lost packets in the initial round by leveraging the broadcasting nature of wireless transmissions. This observation is consistent with that from simulation results.

VI. CONCLUSIONS

In this paper, we considered a one-hop underwater acoustic network where one destination node collects data from multiple underwater nodes. We developed two protocols, selective relay cooperation and dynamic network coded cooperation, where nodes overhearing the transmissions from other nodes help to deliver the missing packets to the destination based on relay operation and network coding, respectively. In addition to simulation results, the conventional ARQ and the proposed SRC and DNC protocols were implemented and tested in a lake environment. The benefit of dynamic node cooperation has been validated.

Future work could couple the node cooperation with power control or adaptive modulation and coding to minimize the energy consumption or prolong the network lifetime.

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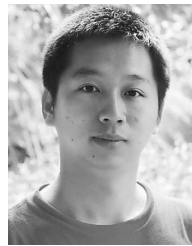
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