Dynamic Joint Network-Channel Coded Cooperation for Underwater Data Collection

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Abstract—**In this paper, we propose dynamic joint network-channel coded cooperation (DJNCC), for an underwater data collection problem, where multiple underwater nodes need to send data to one common destination. DJNCC seamlessly couples channel coding and dynamic network coded cooperation (DNC) to effectively combat the detrimental effect of fading of underwater channels, utilizing the fact that underwater nodes can overhear the transmission of others and relay each other when necessary. The relay-nodes participating in the cooperation are selected by the destination based on the measured pilot signal to noise ratio of the underlying OFDM modulation. Through both analysis and simulation for one specific underwater topology, we demonstrate the significant performance improvement of DJNCC over other schemes.**

Keywords- Joint network-channle coded cooperation; OFDM; Dynamic coded cooperation;Underwater acoustic networks

I. INTRODUCTION

In large-scale underwater acoustic (UWA) sensor networks, to monitor phenomena in underwater environments, one research issue is to design effective approaches for one central node to collect the data from multiple underwater sensors [1-3]. Compared to wireless radio communications, UWA communications suffer from high and space-time-frequency-varying packet losses due to the detrimental effect of fading of UWA channels [4-6]. Some effective methods to provide reliable communication are using *error correction* codes inside a packet at physical layer (channel coding) or *erasure correction* codes across multiple packets at network layer (network coding) or both (joint network-channel coding) [7-8].

Existing topology networks related to the data collection design protocols can be roughly classified into the following two categories: *homogeneous networks* and *heterogeneous networks*. In the former case, all the communication channels, either from a terminal to the destination or between two terminals, are spatially independent and have the same signal-to-noise ratio (SNR). The adaptive network coded cooperation (ANCC) [1] and the generalized adaptive network coded cooperation (GANCC) [2] are proposed for this network where the coding structure matches well with the network topology. In the later case, selective relay cooperation (SRC) and dynamic network coded cooperation (DNC) [3] are proposed to combat the case when only parts of the nodes are dynamically participating in the cooperation phase instead of all due to individual channel characteristics (SNRs). However, if there was only one undecoded node left, the DNC scheme then deteriorates into SRC scheme and no more benefit can be obtained from joint iterative decoding among nodes, i.e., there is no network coding gain in this case. Actually, the higher collection rounds, the fewer undecoded nodes left, which lead to less network coding gain for DNC scheme. Hence we consider coupling the physical layer channel coding and the network layer DNC scheme to combat this issue.

In this paper, we propose dynamic joint network-channel coded cooperation (DJNCC), to increase the overall system performances, combining the physical layer channel coding gain at the first round and the DNC scheme. At the physical layer, we also consider OFDM modulation [9] as our previous work in [3], where the SNR can be effectively measured at the pilot sub-carriers. The transmission schedules are also optimized by the destination based on the pilot SNRs from the nodes to the destination and the side information on what packets from other nodes are available at each relay. The main difference lies in the joint network-channel decoding at the destination.

The rest of the paper is organized as follows. In Section II, we describe some preliminaries for the proposed DJNCC scheme, including the system model and the related SRC and DNC schemes. We then present the proposed scheme in Section III and show the simulation results of all the schemes as a comparison in Section IV. Finally the conclusions are drawn in Section V.

II. PRELIMINARIES

In this section, we first present the underwater data collection system model, and then present the background on the SRC and DNC schemes about data collection protocols that are previous work in our proposed DJNCC scheme.

A. System Model

The system includes N_u terminals that communicate wirelessly to a common destination. Fig. 1 shows one example where 5 underwater nodes S_1, S_2, S_3, S_4, S_5 send data to a common surface destination D.

For UWA transmissions, we assume that each node uses

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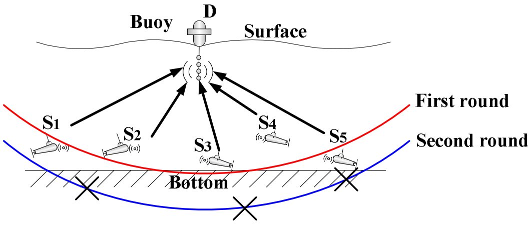

Figure 1. A N_u-to-1 underwater acoustic data-collection system ($N_u = 5$).In the second round, nodes marked "X" do not transmit.

OFDM modulation with a total of K sub-carriers [9]. Let $\boldsymbol{s}_u$ be the $K \times 1$ vector containing the transmitted symbols on the OFDM sub-carriers for node u, and $\mathbf{z}_u$ be the frequency-domain measurement at the destination after necessary Doppler compensation and FFT operation [9]. The input-output relationship from the uth terminal to the destination is

$$\mathbf{z}_u = \mathbf{H}_u \mathbf{s}_u + \mathbf{w}_u \tag{1}$$

where $\mathbf{H}_u$ denotes the channel mixing matrix with size $K \times K$, and $\mathbf{w}_u$ is the ambient noise at the receiver with length $K \times 1$. When the channel is time-invariant, $\mathbf{H}_u$ is diagonal, otherwise, inter-carrier-interference (ICI) occurs and some off-diagonal components of each $\mathbf{H}_u$ are nonzero.

The process diagram for the underwater data collection protocols is shown in Fig. 2. The left part indicates the first round in collection, and the right part indicates the rounds that over one, where the overheard information can be adopted as relays and the collection protocols can be optimized.

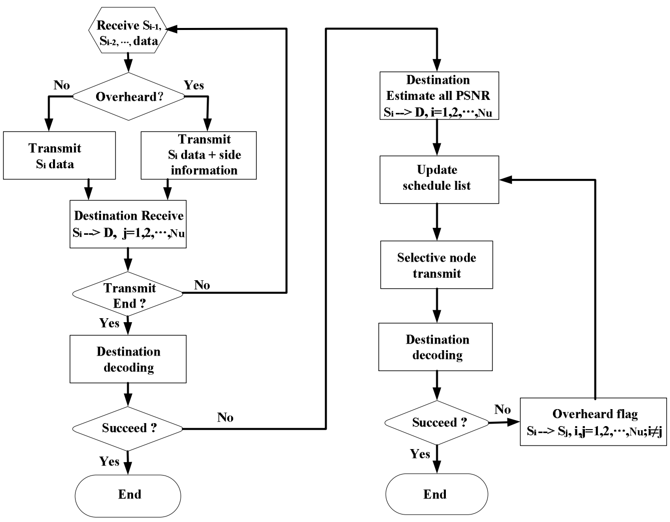

Figure 2. Process diagram for underwater data collection protocols.

B. SRC and DNC Schemes

In the practical *heterogeneous networks,* SRC and DNC schemes are proposed in [3] for underwater data collection protocols. In the SRC scheme, instead of retransmission from the undecoded node itself (known as ARQ scheme), one other node who has overheard the transmission successfully will be selected as a relay for better performance. In the DNC scheme, the selected relay nodes transmit network coded packets, combining the packets from several undecoded nodes to the destination [3]. Fig. 3 shows the schematic diagram for the DNC protocol.

Compared with ARQ scheme, SRC and DNC schemes can dynamically select the relay(s) to help others since the second round. However, both of them do not use the information in the physical layer from the first round. When fewer nodes are undecoded, the network coding gain of DNC is not so significant.

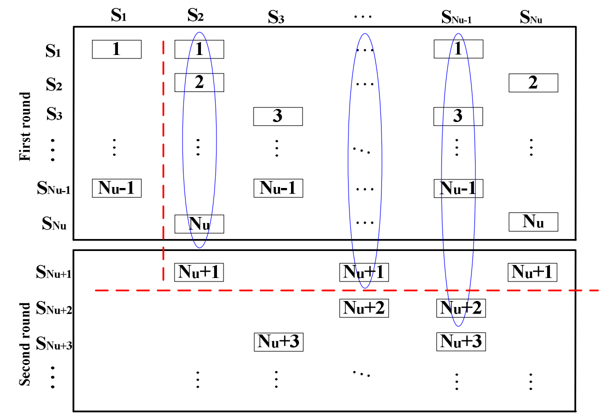

Figure 3. Schematic diagram for the DNC scheme.

III. Dynamic Joint Network-Channel Coded Cooperation Scheme

In this section, we present details of the proposed DJNCC scheme based on DNC scheme in [3].

A. First Round

The first round is identical to the SRC and DNC schemes, except considering the channel coding for node-to-node communication over the UWA channels.

We assume that node $\boldsymbol{s}_u$ generates a packet $\mathbf{x}_u$, then encodes it into $\mathbf{c}_u$ in a finite field using the common generator matrix $\mathbf{G}$ as

$$\mathbf{c}_u = \mathbf{x}_u \cdot \mathbf{G} \tag{2}$$

B. Second Round

There are P nodes in the set S^- that have not been correctly received. The destination now selects P relays in the second round for retransmission, although the protocol can be extended by allowing more than P relays in the cooperation round. Assume that a relay set R is selected, and the kth relay will send

$$\tilde{\mathbf{c}}_k = \alpha_{k,i_1} I_{k,i_1} \mathbf{c}_{i_1} \oplus \alpha_{k,i_2} I_{k,i_2} \mathbf{c}_{i_2} \oplus \cdots \oplus \alpha_{k,i_P} I_{k,i_P} \mathbf{c}_{i_P} \tag{3}$$

where $i_1,\cdots,i_P \in S^-$, and $\{\alpha_{k,i_1},\cdots,\alpha_{k,i_P}\}$ are the coefficients in a finite field. For the uth node, $I_{u,v}$=1 means that it has decoded the data from the vth node, and $I_{u,v}$=0 means otherwise.

To improve the system performance, the relay selection is based on the pilot SNRs as:

$$R^* = \arg\max_R f\left(R, S^-\right)\cdot \sum_{k\in R} \mathrm{PSNR}_k \tag{4}$$

where f (R, S^-) specifies whether the relay set R is a valid relay set for S^-. A valid relay set means that the following set of linear equations are solvable:

$$\begin{bmatrix} \mathbf{c}_{i_1} \\ \vdots \\ \mathbf{c}_{i_P} \\ \tilde{\mathbf{c}}_{i_1} \\ \vdots \\ \tilde{\mathbf{c}}_{i_P} \end{bmatrix} = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \\ \alpha_{k_1,i_1} I_{k_1,i_1} & \cdots & \alpha_{k_1,i_P} I_{k_1,i_P} \\ \vdots & \ddots & \vdots \\ \alpha_{k_P,i_1} I_{k_P,i_1} & \cdots & \alpha_{k_P,i_P} I_{k_P,i_P} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{i_1} \\ \vdots \\ \mathbf{x}_{i_P} \end{bmatrix} \mathbf{G} \tag{5}$$

After collecting the received signals from the second round, iterative channel and network decoding as in [8] can be applied to decode all the missing packets from the nodes in S^- simultaneously.

C. Further Rounds

Similar procedures as in the second round are carried out, except that the information table [3] is updated.

IV. NUMERICAL RESULTS

In this section we perform simulations to analyze the performance of DJNCC compared to SRC and DNC schemes.

A. Simulation Setup

We use one specific geographical topology, and the relative distances among nodes are collected in Table I. In the first round, the destination schedules S_1 to transmit first, and S_5 to transmit last, according to the distances to the destination.

TABLE I. DISTANCES AMONG NODES FOR THE UWA NETWORKS

*d**	S_1	S_2	S_3	S_4	S_5	*D*
S_1	0.00	1.75	2.50	4.00	4.25	5.75
S_2		0.00	2.75	3.75	3.00	5.00
S_3			0.00	1.75	3.25	3.75
S_4				0.00	2.75	2.50
S_5					0.00	2.25

* Unit: km

The OFDM parameters are chosen as in [9], with the number of OFDM sub-carrier K=1024. The multipath channels are randomly generated with 50 taps in the baseband, and are assumed as quasi-static fading. We use E_s to denote the symbol energy and N_0 the noise variance on each OFDM sub-carrier. The average pilot SNR is proportional to E_s/N_0, but weighted by the propagation losses at different distances, which is as

$$\mathrm{PSNR}[k] = \left|H[k]\right|^2 \cdot E_s/N_0 \tag{6}$$

where $H[k]$ is the channel complex equivalent factor. The average energy of the channel from node S_5 to the destination is normalized to be one, and is a function of distance d as

$$\left|H[k]\right|^2 \propto d^{-1.5} \tag{7}$$

which is assumed to determine the average energy of other channels.

Instead of a practical code, here we assume capacity-achieving codes and use the mutual information (MI) to evaluate the outage probabilities of whether a packet can be decoded correctly at the receiver. For the node-to-node transmission with K OFDM sub-carrier, MI is as

$$MI = \frac{1}{K}\sum_{k=-K/2}^{K/2-1} \log_2\left(1+\left|H[k]\right|^2 \cdot E_s/N_0\right) \tag{8}$$

An outage occurs if the total mutual information at the destination after the dynamic coded cooperation is lower than the information rate r, which is as

$$p^{out} = \Pr\{MI < r\} = \Pr\left\{\frac{1}{K}\sum_{k=-K/2}^{K/2-1} \log_2\left(1+\left|H[k]\right|^2 \cdot E_s/N_0\right) < r\right\} \tag{9}$$

We set the information rate as 0.5 bit/symbol in the simulation.

B. Performances of DJNCC and other schemes

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, i.e.,

$$p_{all}^{out} = 1 - \prod_{i=1}^{N_u}\left(1 - p_i^{out}\right) \tag{10}$$

where p_i^{out} is the outage probability for node S_i(i=1,2,…,N_u) to the destination.

Fig. 4 shows the overall outage probability of the system for DJNCC scheme and other schemes, where the proposed DJNCC scheme has about 1 dB gain compared with the DNC scheme in [3], and about 4 dB gain compared with SRC scheme. As shown in Fig.4, for the DJNCC scheme, using three rounds brings additional 1 dB gain compared with using two rounds. Yet for the SRC or DNC scheme, this benefit from the additional rounds decreases to less than 0.8 dB. Especially, for the DNC scheme, there is only less than 0.5 dB gain. This is because higher round means fewer undecoded nodes, lead to performance bottlenecks for DNC scheme but not for DJNCC scheme.

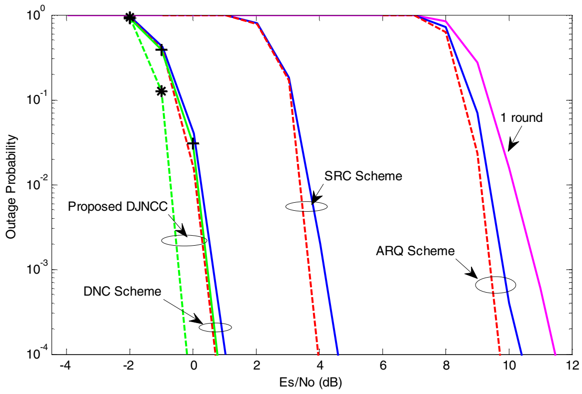

Figure 4. The overall outage probability for DJNCC and other schemes. Dash lines: a maximum of 3 rounds; Solid lines: a maximum of 2 rounds.

On the other hand, performance of DJNCC scheme with 2 rounds is close to that of DNC scheme with 2 or 3 rounds. Performance of DJNCC scheme with 3 rounds is much better than that with 2 rounds, which is because DJNCC scheme can use the physical layer channel coding information to improve the system performances, even there are fewer undecoded nodes along with the rounds increase.

V. CONCLUSIONS

In this paper, to overcome the performance bottlenecks for DNC scheme caused by fewer undecoded nodes, we investigated a practical OFDM modulated DJNCC scheme for underwater data collection, coupling channel coding at the physical layer and DNC scheme. Compared with the previous work (SRC and DNC protocols), numerical results showed that the DJNCC protocol can improve the system performance significantly through node cooperation and channel coding.

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