Dynamic Block-Cycling Over A Linear Network in Underwater Acoustic Channels

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ABSTRACT

The underwater acoustic (UWA) environment is known to have large spatial and temporal variations. In this paper, we propose a dynamic cooperative relaying protocol, termed dynamic block-cycling (DBC) protocol, for a UWA linear network. Considering large channel variations, we assume one node can hear from not only its direct but also several remote neighbors. A transmission package with multiple blocks is taken as one relay unit, where an erasure-correction code and an error-correction code are used for inter-block encoding and intra-block encoding, respectively. During the relaying process, each node in the proposed protocol starts relaying immediately after it decodes the relayed message, hence a reduced end-to-end transmission latency can be achieved. Meanwhile, to avoid the overhead for relay cooperation, the relays' transmissions are cyclically synchronized, such that in each time slot, the blocks arriving at the downstream receiving nodes from all the upstream transmitting nodes have the same block index. Numerical results show that for a one-shot transmission, the proposed protocol achieves a reduced end-to-end delay relative to existing protocols while maintaining a decent outage performance.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Network communications; H.4 [**Information Systems Applications**]: Communications Applications

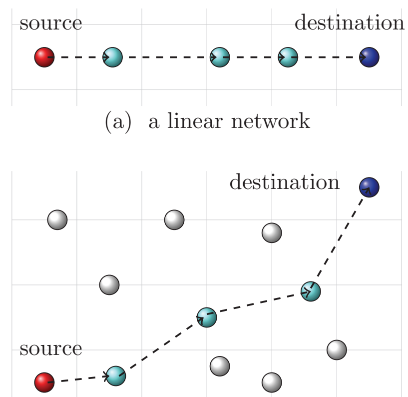
General Terms

Algorithms, Design, Performance

Keywords

Linear network, dynamic block-cycling, end-to-end delay, network throughput, underwater acoustic channel.

1. INTRODUCTION



(a) a linear network

(b) an *ad hoc* network

Figure 1: Relaying over the underwater acoustic networks, dashed line denoting the relaying route.

Recently, underwater acoustic (UWA) communications and networking have drawn considerable attention. Progress on UWA networking can be found in, e.g. [1,2]. Existing protocols for UWA networks mainly operate in a single-hop or hop-by-hop fashion, with the goal of increasing the data transfer reliability and the network throughput.

In this work, we are interested in reducing the end-to-end transmission delay for delay-sensitive applications, such as remote sensor monitoring and submarine detection [2, 3]. Particularly, we consider a UWA linear network with a source and a destination at the two ends and multiple relay nodes in the middle; as illustrated in Fig. 1(a), and all the nodes operate in the half-duplex mode.

Extensive investigation on wireless networking has been carried out in the last several decades [4–6]. Existing relaying strategies mainly fall into two categories, i) multihop relaying formed by hop-to-hop transmissions, as illustrated in Fig. 2(a); and ii) the cooperative relaying which relies on the cooperative transmission of multiple relay nodes; illustrated in Fig. 2(b) is one example termed turbo relaying, which is proposed in [6].

Specific to the UWA channel, preliminary works on network relaying strategies can be found in [7,8]. In [8], a hop-by-hop transmission protocol was investigated for a regular linear UWA network, in which the optimal spatial reuse factor and spectrum shaping to account for frequency-dependent attenuation were discussed. In [7], the error propagation in both cooperative and multihop transmissions over the regular linear network and the regular plenary network was ex-

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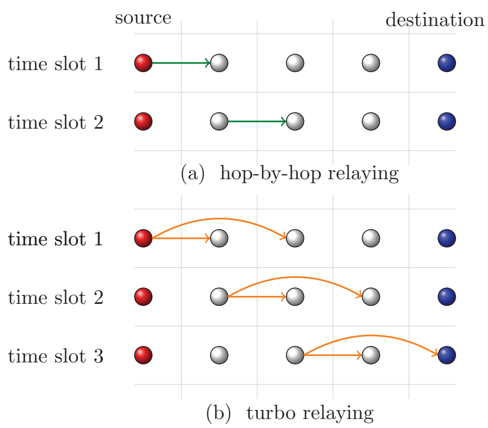


Figure 2: Illustration of two relaying strategies over a linear network.

amined, in which the two schemes were shown to outperform the single-hop transmission considerably.

Given variations of UWA channels, it may not be advantageous to maintain a fixed data rate or a fixed cooperation strategy. One viable solution to adapt to channel variation is to use rateless coding to achieve both reliability and a reasonable data rate [9]. However, as this scheme requires full duplex operation and also feedback from the receiver, its applicability is limited due to the half-duplex constraint of current underwater communication hardware and the low propagation speed of acoustic waves in underwater.

To address challenges posed by UWA channels, we propose a dynamic cooperative relaying protocol, termed dynamic block-cycling (DBC) protocol, to reduce the end-to-end transmission latency in the *one-shot* transmission, i.e., the relaying of a single transmission packet. Adopting a layered erasure- and error-correction channel coding scheme for information bits encoding, numerical results show that the DBC protocol outperforms existing protocols in terms of the end-to-end transmission latency while maintaining a decent outage performance.

We would like to highlight that the proposed scheme can be applied to other types of networks, such as the *ad hoc* network for individual routes as illustrated in Fig. 1(b). Its application to continuous transmission with spatial reuse is of practical interest and warrants further investigation; a higher throughput can be expected given that the proposed protocol reduces the end-to-end transmission latency relative to existing schemes in the one-shot transmission.

The rest of the paper is organized as follows. The proposed dynamic relaying protocol is introduced in Section 2. Discussions on the proposed protocol are provided in Section 3. Simulation results are described in Section 4. Section 5 concludes the paper.

2. DYNAMIC BLOCK-CYCLING (DBC)

We consider a linear network with $(M+1)$ nodes. The first node indexed by 0 is the source, and the last node indexed by M is the destination. The nodes between the source and destination indexed by $1, 2, \cdots, M-1$ are relay nodes. We assume that all the nodes operate in the half duplex mode.

2.1 Dynamic Block-Cycling Transmission

We assume burst-based transmissions. Each burst consists of $N_{\rm bl}$ blocks. Each block can be an orthogonal-frequency division-multiplexing (OFDM) block as explained in Section 2.3. A layered channel coding scheme is adopted [10], in which an erasure-correction channel code is applied over the $N_{\rm bl}$ blocks for the inter-block encoding and an error-correction channel code is applied within each block for the intra-block encoding. Depending on the link quality, information bits in each burst can be deciphered with a variable number of received blocks. During the relay process, we assume that all the nodes use the same codebook.

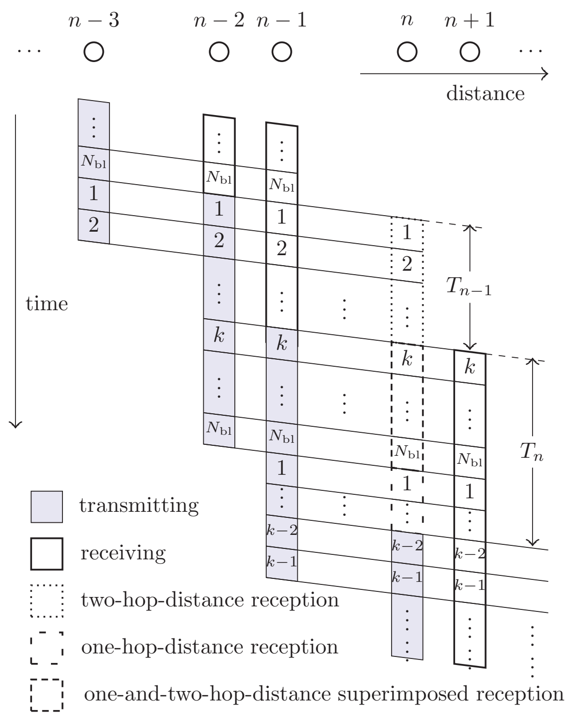


Figure 3: Illustration of the cyclically synchronized transmission over a non-equally spaced linear network at node n with three temporal progressive listening phases. Two-hop communication distance is assumed as an example.

To relay $N_{\rm bl}$ coded blocks from source to destination, the proposed protocol incorporates two strategies.

- *Instantaneous transmission upon successful decoding:* To reduce the latency, each relay node attempts burst decoding and performs parity check when receiving one more block; *immediately after* the information bits within one burst are successfully recovered, it regenerates the coded transmission blocks and relays the message to downstream nodes.
- *Cyclically synchronized transmissions:* To remove the coordination overhead between the transmitting and receiving nodes, the transmitted block-indices from one node are cyclically synchronized with those transmitted by the upstream nodes, as illustrated in Fig. 3. Specifically, when one node starts transmission, the transmitted blocks have the same indices as the blocks that it would have heard from its upstream nodes shall it stay in the receiving mode (denote its first transmitted block index as k). *Superposition of signals starts right at the relay point, and the signal at a downstream*

receiving node can be taken as the signal from single source but passing through a composite channel containing multiple paths.[1] Once a node finishes transmission of the block with index $N_{\rm bl}$, it continues to transmit the blocks with indices $1, \cdots, (k-1)$, completing the transmission of $N_{\rm bl}$ coded blocks in total.

Two special examples of proposed protocol are in order.

- In the scenario with a large transmission power such that the destination can directly hear the source, the DBC protocol enables an end-to-end transmission, thus avoids the latency in the hop-by-hop relaying;
- In the scenario with a small transmission power such that one node can only hear its direct neighbor, the DBC protocol becomes the classical hop-by-hop relaying protocol.

2.2 Decoding at the Relay Node

At the relay node, two decoding approaches can be used.

- *Layered decoding:* Corresponding to the layered encoding, blocks within one transmission burst are decoded in two steps. Firstly, each block is decoded individually corresponding to the error-correction code. Any block with decoding errors will be discarded. Secondly, the erasure-correction decoding is performed to recover the information bits. The discarded blocks in the first step are treated as erased by the channel.
- *Joint decoding:* The received blocks with the layered encoding can be jointly decoded based on the maximum-likelihood criterion. The decoding operation can be achieved via, e.g., belief propagation. Despite its good decoding performance, the computational complexity is significantly higher, especially when $N_{\rm bl}$ is large.

2.3 One Implementation Example With OFDM

To solve the synchronization issue of multiple paths in UWA channels, we take OFDM for block modulation [12]. A Reed-Solomon (RS) code [13] and a low-density parity-check (LDPC) code can be used for inter- and intra-block encoding, respectively. Notice that the relay node requires knowledge of received block indices for data decoding. With the dynamic cyclically synchronized transmission, we embed the transmitted block index as a header into the information delivered by each block. By successfully decoding any single received block, indices of all the received blocks at the relay node can be recovered. Since the header size is very limited, the overhead incurred by the cyclically synchronized transmission is almost negligible.

3. DISCUSSION OF THE DBC PROTOCOL

3.1 Appealing Features

Tailored to the UWA channel characteristics, the DBC protocol possesses the following desirable features:

- *Transmission latency adaptation based on link quality:* The proposed protocol adapts its transmission schedule according to link dynamics. Specifically, for the node with good link quality, it only requires a small number of receiving blocks from upstream transmitters for successful decoding, hence can quickly relay the message to the downstream nodes. For the node with low link quality, a large number of receiving blocks for successful decoding is necessary, so as to maintain a high reliability.
- *Simplicity of implementation:* Given the spatial and temporal variations of UWA channels, the number of transmitting nodes and the transmission schedule during one burst transmission are dynamic. With the cyclically synchronized transmission, the receiving nodes can be oblivious of the number of transmitting nodes and their transmission schedule. This eliminates the coordination overhead of the cooperative relaying.
- *Synchronization at transmitting nodes:* With each node aligning its transmission with the signal it hears from upstream nodes at its own position, the cyclically synchronization transmission enables the synchronization of signals from different transmitters at the receiving node; see Fig. 3. *The signal superposition starts right at the transmitting relay node, and signal synchronization at one downstream receiver from multiple transmitters does not depend on the node distance. The proposed protocol hence applies to a linear network with non-equally spaced nodes.*

3.2 End-to-End Delay

The end-to-end delay consists of the transmission latency and the propagation delay

$$T_{\rm e2e} = T_{\rm trans} + T_{\rm prop} \tag{1}$$

where the propagation delay $T_{\rm prop}$ is equal to the end-to-end distance divided by the sound speed in water, and the transmission latency can be expressed as

$$T_{\rm trans} = \sum_{n=1}^{M} T_n \tag{2}$$

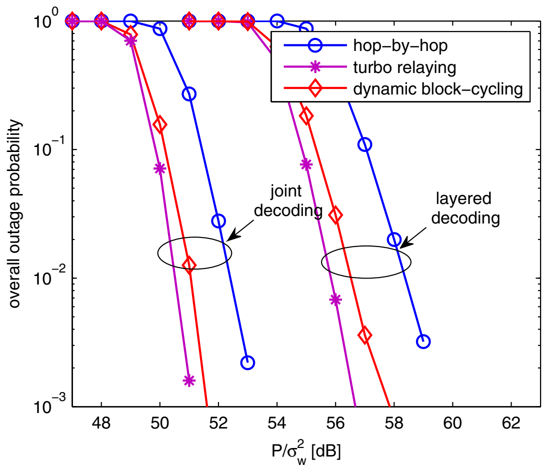
with T_n denoting the transmission time offset of node n relative to node $(n-1)$ in the unit of block time-duration (c.f. Fig. 3). Note that the transmission of node n can be prior to that of node $(n-1)$ due to the cooperative transmission. As a result, the offset can be negative.

Assume that one node can hear from several of its upstream nodes. After incorporating the signal one node overhears from the nodes beyond its direct neighborhood into the decoding process, the offset T_n is expected to be smaller than that without using the overheard signal. Moreover, the proposed protocol adapts the transmission latency according to the link quality, whereas the classic hop-by-hop relaying has a fixed offset $N_{\rm bl}$. Hence, a reduced end-to-end transmission latency can be achieved in the proposed protocol relative to the classic hop-by-hop relaying protocol.

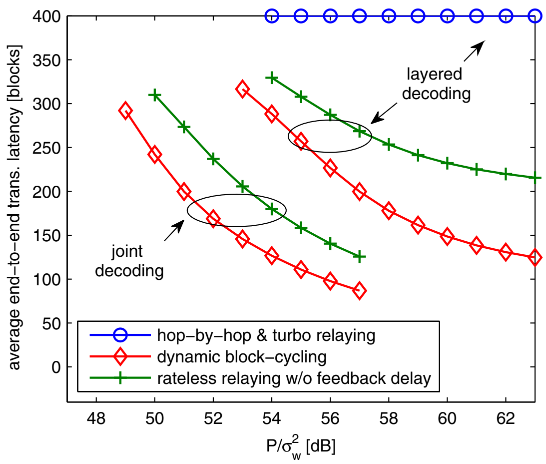
4. NUMERICAL RESULTS

We consider a linear network with $M+1 = 21$ nodes, and the distance between consecutive nodes is $d = 2$ km, except that the distance between the source and its next node is set as $d/2 = 1$ km for initiating the cooperative transmission. In each burst, there are $N_{\rm bl} = 20$ blocks which are erasure-correction coded over $I_{\rm bl} = 10$ information blocks. The system center frequency is $f_{\rm c} = 10$ kHz. The channel

[1] In this paper, we focus on a stationary linear network. In a mobile network, given that the received signal consists of signals from multiple distributed transmitters, the Doppler effects of these signals could be quite different if different transmitters have different platform motions; a receiver design tailored to this scenario can be found in, e.g., [11].



(a) outage probability



(b) average end-to-end transmission latency

Figure 4: Performance comparison of several relaying protocols with two decoding schemes.

is assumed Rayleigh faded, and is generated individually for each block transmission.

Three relaying strategies are considered for comparison: i) the classical hop-by-hop relaying protocol, ii) the turbo relaying protocol proposed in [6], and iii) the proposed dynamic block-cycling protocol. We examine the outage probability and the average end-to-end transmission latency of these strategies in the one-shot transmission, and assume a two-hop communication range. 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, none of its downstream nodes within its communication range can recover the relayed message. To compute the end-to-end transmission delay in (2), the transmission offset T_n is obtained as the minimum number of receiving blocks node n requires for successful message recovery after node $(n-1)$ starts transmission.

Define the transmission signal-to-noise ratio (SNR) as the

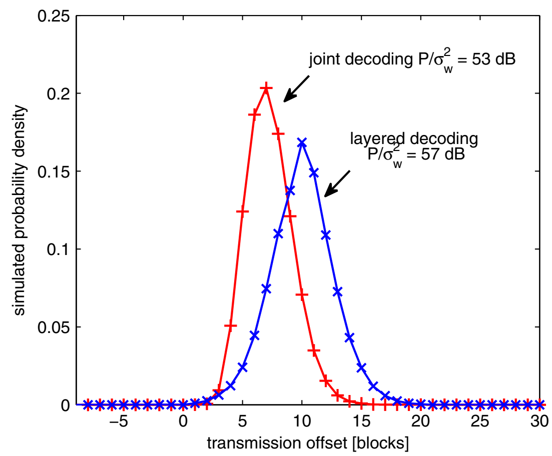


Figure 5: Simulated distribution of transmission offset in the proposed protocol.

transmission power over the ambient noise variance, i.e., $\bar{\gamma} := P/\sigma_{\mathrm{w}}^2$. Denote $\sigma_d^2(f)$ as the attenuation of the signal at frequency f after transmitting a distance d,

$$\sigma_d^2(f) := e^{-\alpha(f)d} d^{-\beta}, \tag{3}$$

where $\alpha(f)$ is the frequency-dependent absorption coefficient, and β is the path-loss exponent which is taken as 1.5 in the practical system; see [14, Eqs. (1-3)] for details. The received SNRs during the periods of two-hop reception, one-and-two-hop superimposed reception and one-hop reception in Fig. 3, are related to the transmission SNR according to

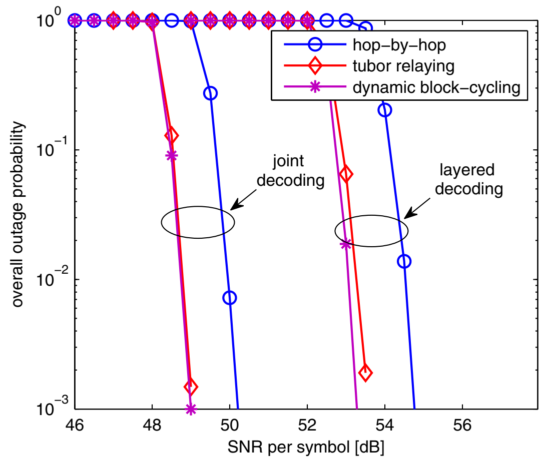
$$\begin{cases} 10\log_{10}\bar{\gamma}_{\text{two-hop}} = 10\log_{10}\bar{\gamma} + 10\log_{10}\sigma_{2d}^2(f), \\ 10\log_{10}\bar{\gamma}_{\text{superimp}} = 10\log_{10}\bar{\gamma} + 10\log_{10}[\sigma_{2d}^2(f) + \sigma_d^2(f)], \\ 10\log_{10}\bar{\gamma}_{\text{one-hop}} = 10\log_{10}\bar{\gamma} + 10\log_{10}\sigma_d^2(f). \end{cases}$$

For $d = 2$ km, and $f = 10$ kHz, we have $10\log_{10}\sigma_{2d}^2(f) = -58.8$ dB, $10\log_{10}\sigma_d^2(f) = -51.9$ dB, and $10\log_{10}[\sigma_{2d}^2(f) + \sigma_d^2(f)] = -51.1$ dB.

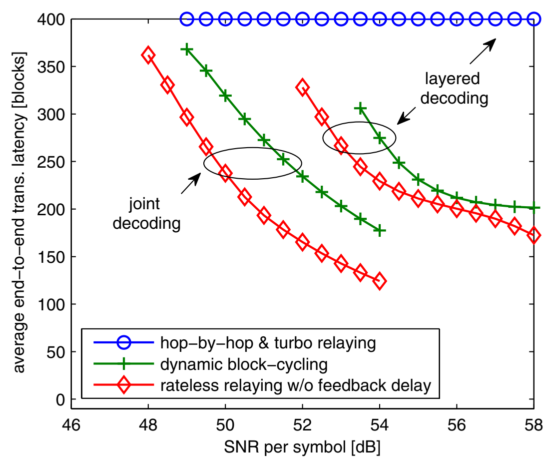
4.1 Narrowband System

For the narrowband system operating at one frequency point with a block data rate $R_{\mathrm{bl}} = 1$ bit/sec/Hz, Fig. 4(a) demonstrates the simulated outage probabilities of three relaying strategies. One can see that for both decoding schemes, turbo relaying achieves the best outage performance, the proposed scheme is slightly worse than turbo relaying, and both of them outperform the hop-by-hop relaying due to the cooperative operation.

Averaged over channel dynamics, Fig. 4(b) shows the end-to-end transmission latencies T_{trans} of the three relaying strategies. The end-to-end transmission latency of the hop-by-hop relaying protocol equipped with the rateless coding with instantaneous feedback [9] is also plotted, where the instantaneous feedback assumption is actually not realistic, but the result can be taken as the performance bound of the hop-by-hop relaying scheme. From Fig. 4(b), one can see that the proposed method outperforms the rateless coded hop-by-hop relaying via the transmission latency adaptation. Moreover, for the layered decoding, the end-to-end transmission latency of the rateless relaying is lower



(a) outage probability



(b) average end-to-end transmission latency

Figure 6: Performance comparison of several relaying protocols with two decoding schemes.

bounded by $MI_{\rm bl}$, while the proposed protocol avoids this lower bound with the cooperative transmission.

Fig. 5 demonstrates the simulated probability density function of the transmission offset T_n in the proposed protocol for two decoding schemes. Compared with the hop-by-hop and turbo relaying with an offset of $N_{\rm bl}$, a lower transmission offset T_n in the proposed protocol leads to a reduced end-to-end transmission latency.

4.2 Wideband System

We consider a wideband system consisting of seven subchannels within a frequency band $7 \leq f \leq 13$ kHz. With a block rate $R_{\rm bl} = 7$ bits/symbol, Fig. 6(a) shows the simulated outage probabilities of three relaying strategies. Compared to the narrowband system, the gap between turbo relaying and the proposed protocol is decreased, and the wideband system shows a larger diversity order. Meanwhile, relative to the narrowband system, the performance difference between the joint decoding and the layered decoding decreases from 6 dB to about 3.5 dB. Similar to the observation in the narrowband system, Fig. 6(b) shows that the proposed protocol achieves the minimal end-to-end transmission latency among all the protocols under consideration.

5. CONCLUSIONS

In this paper, we proposed a dynamic cooperative relaying protocol for a linear network in UWA channels. Due to UWA channel characteristics, such as the long acoustic signal propagation delay and large spatial and temporal variations, existing protocols for the terrestrial radio network may suffer great performance degradation. Building on a layered erasure- and error-correction coding scheme and the cooperative relaying strategy, the proposed protocol achieves transmission schedule adaptation without requiring feedback from the receiver. Compared to existing protocols, it enjoys a much reduced end-to-end transmission delay.

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