On Applying Network Coding to Underwater Sensor Networks

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ABSTRACT

High error rates and long propagation delays in underwater sensor networks call for efficient error-recovery schemes. We believe network coding is a promising technique for this purpose because of the broadcast nature of acoustic channels and computation capabilities at the sensor nodes. In this paper, we design a network coding scheme for underwater sensor networks and explore its performance through simulation. Our initial results indicate the benefits of using network coding for error recovery and the gains from coding at the source.

Categories and Subject Descriptors

E.4 [**CODING AND INFORMATION THEORY**]: Error control codes; H.1.1 [**MODELS AND PRINCIPLES**]: Systems and Information Theory—*Information theory*

General Terms

Reliability, Design, Performance

Keywords

Network Coding, Under-Water Sensor Networks, Error Recovery, Multipath Routing

1. INTRODUCTION

Underwater sensor networks are ideal vehicles for monitoring aqueous environments. However, before the wide deployment of underwater sensor networks becomes a reality, a range of challenges must be tackled [1, 2, 3]. One such challenge is efficient error recovery in the presence of high error rates and long propagation delays (caused by slow acoustic communication). Using common error-recovery techniques such as Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) in underwater sensor networks has the following drawbacks. ARQ-based schemes require the receiver to detect losses and then request the sender to retransmit packets. This may lead to long delays to deliver a packet successfully to the receiver due to the long propagation delays in underwater sensor networks. FEC-based schemes proactively add redundant packets to eliminate retransmission from the source. The amount of redundancy needs to be sufficient to recover losses while conserving the limited battery power of the sensor nodes. Determining the right amount of redundancy is, however, a challenging task due to the difficulty to obtain accurate error-rate estimates [3].

We believe network coding is a promising technique for efficient error recovery in underwater sensor networks. This is because underwater sensor nodes are usually larger than land-based sensors and posses more computational capabilities [4]. Futhermore, the broadcast property of acoustic channels naturally renders multiple routes from a source to a destination. The computational power at the sensor nodes coupled with the multiple routes provides ample opportunities to apply network coding: the source and intermediate nodes may encode packets and send the packets on multiple routes; the destination may combine incoming packets from multiple routes to recover the original data. In this paper, we explore error recovery through network coding in underwater sensor networks.

Network coding was first proposed in [5]. Since then, it has found applications in many areas including multicast, content distribution, wireless networks, network security, and distributed storage (see [6] and the references within). The main idea of network coding is that, instead of simply forwarding a packet, a node may code several incoming packets into one or multiple outgoing packets. We illustrate the usage of network coding in underwater sensor networks in Fig. 1(a). The source sends packets A, B and C to the receiver. These packets will reach relays R_1, R_2 and R_3 because of the broadcast property of acoustic channel. Relay R_1 receives packet A and C and encodes them into packets Y_{11} and Y_{12}. Similarly, relays R_2 and R_3 encode their incoming packets into packets Y_{21}, Y_{22} and Y_{31}, Y_{32} respectively. The relays then forward the encoded packets to the receiver. The receiver receives three encoded packets Y_{11}, Y_{21}, and Y_{31}. When the network coding is chosen properly (e.g., when using linear randomized coding [7]), the receiver can recover the three original packets with high probability. Fig. 1(b) illustrates the results when the relays simply forward the incoming packets without using network coding. In this case, the receiver only receives two distinct original packets.

Our main contributions are as follows. We design a network coding scheme for underwater sensor networks and evaluate its performance through simulation. Our initial results indicate that network coding is indeed a promising technique for efficient error-recovery in underwater sensor networks. Our results also demonstrate the importance to couple network coding and routing carefully as well as the gains from encoding at the source.

The rest of the paper is organized as follows. In Section 2, we describe a network coding scheme for underwater sensor networks. Section 3 presents our initial results. Section 4 concludes this paper and presents future work.

2. NETWORK CODING SCHEME

The high error rates in underwater sensor networks imply that a

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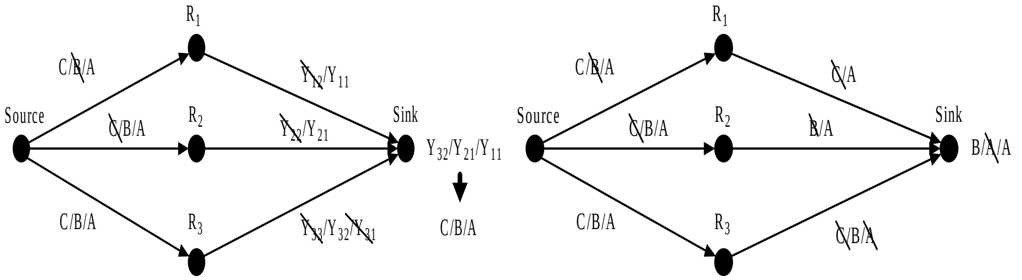


(a) Using network coding.

(b) Not using network coding.

Figure 1: An example illustrating the benefits of using network coding in underwater sensor networks.

certain amount of redundancy is required to recover packets at the receiver. On the other hand, the limited battery power of the sensor nodes imply that the amount of redundancy needs to be restricted to conserve the lifetime of the sensor nodes. Therefore, network coding in underwater sensor networks needs to strike a balance between the amount of redundancy and power conservation at the sensor nodes. We next design a network coding scheme for underwater sensor networks. Throughout this paper, we use linear randomized coding [7] due to its simplicity.

For ease of exposition, we first assume that there is a single source-destination pair in the network; coding for multiple source-destination pairs is described at the end of this section. The routes from the source to the destination are determined by a routing protocol for underwater sensor networks. We use routing protocols that provide multiple paths/routes from the source to the destination, e.g., Direct Diffusion Routing [8], Vector-based Forwarding (VBF) [4]. The intermediate nodes on the routes are referred to as *relays*. Suppose that network coding is applied to k packets from the source, denoted as $X_1, \ldots, X_k$. The source linearly combines these packets to compute k' ($k' \geq k$) outgoing packets, denoted as $Y_1, Y_2, \ldots, Y_{k'}$, where

$$Y_i = \sum_{j=1}^{k} g_{ij} X_j$$

The coefficient g_{ij} is picked randomly from a finite field F_q, where q is the size of the field. The set of coefficients $(g_{i1}, \ldots, g_{ik})$ is referred as the *encoding vector* for Y_i [6]. Each packet to be transmitted in the network carries its encoding vector. The source determines the amount of redundancy that it injects into the network by determining k'. When the source simply forwards the k packets, we have $k' = k$ and $g_{ij} = 1, j = i, g_{ij} = 0, j \neq i$.

A relay stores incoming packets in a local buffer for a certain period of time and then linearly combines the packets in the buffer. Suppose a relay, r, receives m incoming packets, $X_1^r, \ldots, X_m^r$. Let $(f_{i1}, \ldots, f_{ik})$ denote the encoding vector carried by X_i^r, $i = 1, \ldots, m$. Relay r computes m' outgoing packets, $Y_1^r, \ldots, Y_{m'}^r$ by linearly combining the incoming packets. That is, $Y_i^r = \sum_{j=1}^{m} h_{ij}^r X_j^r$, $i = 1, \ldots, m'$. The coefficient h_{ij} is picked randomly from the finite field F_q. Let $(g_{i1}^r, \ldots, g_{ik}^r)$ denote the encoding vector for Y_i^r. Then $g_{ij}^r = \sum_{l=1}^{m} h_{il}^r f_{lj}$. The relay determines the amount of redundancy that it injects into the network by determining m'.

Decoding at the receiver is straightforward: when the receiver receives k packets with linearly independent encoding vectors, it recovers the original k packets by matrix inversion [6].

So far, we have assumed that there is a single source-destination pair. When there are multiple source-destination pairs, we assign a unique node ID to each node. Packets from a source carries the node ID of that source. At the relays, network coding only applies to packets from the same source. When a source has a sequence of n packets, $n > k$, the packets are grouped into so-called *generations*. Each generation contains k packets. Network coding is only applied to packets in the same generation.

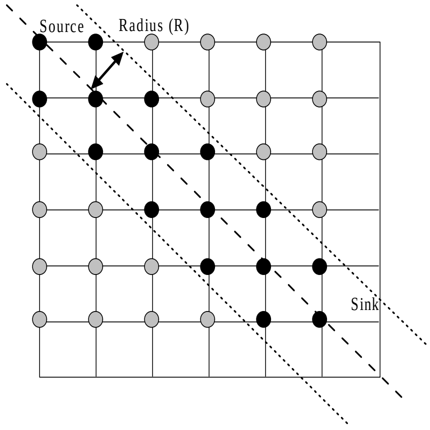
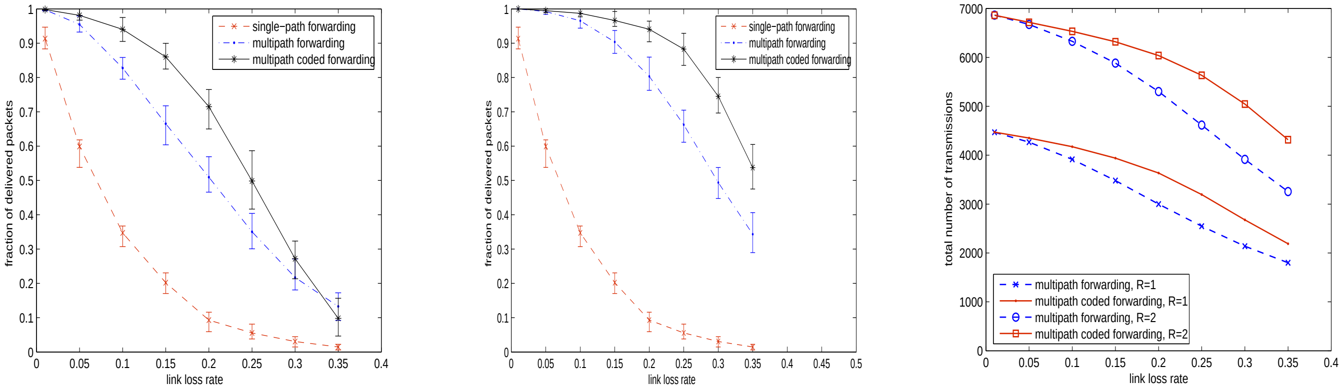


Figure 2: Simulation setting: the source is at (1,1), the destination is at (6,6), and nodes inside the routing pipe radius are highlighted.

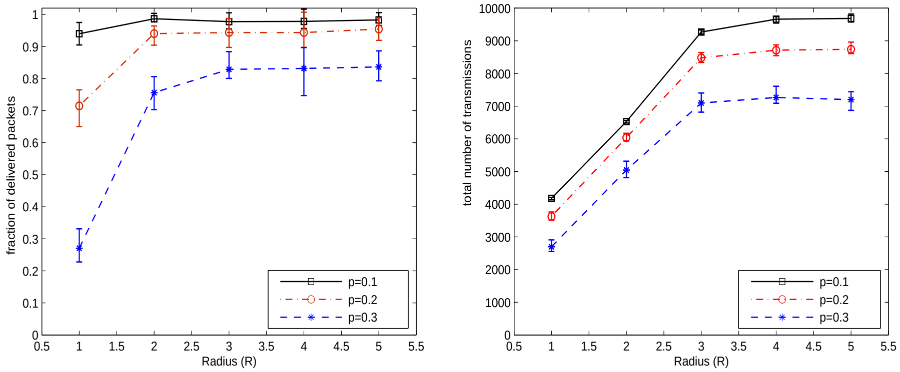
3. SIMULATION RESULTS

In this section, we present our initial results on applying network coding to underwater sensor networks. We simulate a 6×6 grid network as shown in Fig. 2. Two nodes within their transmission ranges are connected by an edge. We denote a node using its corresponding row and column. For instance, the top-left node is denoted as node (1,1) and the bottom-right node is denoted as node (6,6). We assume a single source-destination pair. The source is node (1,1) and the destination is node (6,6). The MAC layer supports broadcasting. The routes from the source to the destination is determined by Vector-based Forwarding (VBF) [4]. In VBF, a *routing pipe* is a pipe centered around the vector from the source to the destination. Nodes inside the routing pipe are responsible for routing packets from the source to the destination; nodes outside the routing pipe simply discard all incoming packets. The radius of the routing pipe is denoted as R. When $R = 1$, the source broadcasts packets to nodes (1,2) and (2,1), which forward the packets to their neighbors. Eventually, nodes (5,6) and (6,5) forward packets to the destination (6,6). We assume that the propagation delays of all the links are the same, of unit 1. Furthermore, all links have the same loss probability, denoted as p. We assume that losses at different links are independent. Furthermore, packet loss due to interference among the nodes is negligible (assuming the interference is addressed in MAC and/or routing layers). Moreover, the relays have sufficient amount of buffer to store incoming packets. The above simplistic settings (e.g., grid topology, homogeneous and independent loss) allow us to obtain analytical results which agree



(a) $R = 1$. (b) $R = 2$. (c) $R = 1, 2$.

Figure 3: The impact of link loss probability on the performance of various schemes.



(a) (b)

Figure 4: The impact of routing radius R on the performance of multipath coded forwarding.

well with simulation results for certain scenarios below. Investigation of more realistic settings is left as future work.

We compare the performance of three schemes: (1) single-path forwarding, (2) multipath forwarding, and (3) multipath coded forwarding. In single-path forwarding, packets from the source are forwarded along a single path to the destination. This path is randomly chosen from the paths provided by the VBF routing protocol. In multipath forwarding, packets from the source are forwarded to the destination along multiple paths determined by the VBF routing protocol. Multipath coded forwarding uses the same set of paths as those in multipath forwarding. However, packets in the network are encoded using the network coding scheme described in Section 2. We use a finite field of size 512.

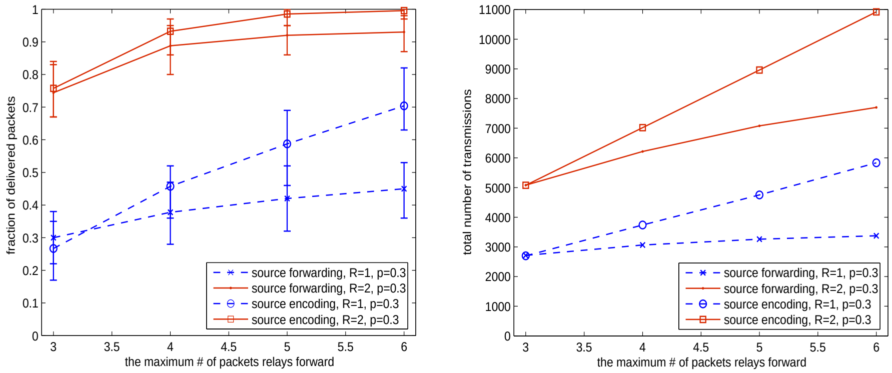
Since efficient error-recovery schemes for underwater sensor networks must achieve high error-recovery rate and conserve sensor node energy simultaneously, we use the following two performance metrics: (1) the fraction of delivered packets, (2) the total number of transmissions from the source and the relays. The first metric measures the quality of error recovery. When using network coding, we say an original packet is delivered to the destination if it can be decoded successfully at the destination. The second metric measures the level of energy consumption. Broadcasting a packet from a source or a relay is counted as a transmission. In our simulation, we assume the source has 300 packets to transmit to the destination. Each generation contains 3 packets. We obtain confidence intervals from 30 simulation runs.

We now present our results. In Section 3.1, network coding is only performed by the relays (i.e., the source simply forwards packets). In Section 3.2, the source also encodes packets. We refer to these two settings as *source-forwarding* and *source-encoding* setting respectively.

3.1 Source-forwarding setting

In this setting, only relays perform network coding. A relay receiving m incoming packets in the same generation will encode them into m' outgoing packets, $m' = \min(k, m)$, where k is the number of packets in a generation. That is, the relays conserve the energy of the network by injecting no more than the number of original packets. For the mulitpath forwarding scheme, a relay discards redundant packets and only forwards distinct packets.

We first investigate the impact of link loss probability on the performance of various schemes. Fig. 3(a) plots the fraction of delivered packets under various schemes when the routing pipe radius in VBF is 1. The link loss rate p is varied in a wide range to account for potential high loss rate in underwater sensor network (e.g., due to fast channel fading). The analytical results (not plotted) for single-path and multipath forwarding match those from the simulation. We observe that as the link loss rate increases, the performance of single-path forwarding degrades much more sharply than that of multipath forwarding or multipath coded forwarding. This indicates the importance of using multiple paths in underwater sensor networks. Multipath coded forwarding outperforms multipath forwarding except when the link loss rate is very high (e.g., $p = 0.35$). The superior performance of multipath coded forwarding is because, in multipath coded forwarding, every packet is a linear combination of the original packets and carries useful infor-



(a) The fraction of delivered packets.

(b) The total number of transmissions

Figure 5: Comparison between source-encoding and source-forwarding settings.

mation for error recovery. However, when the loss rate is very high, the number of received packets at the destination is not sufficient to recover the original packets. Hence less number of packets are delivered under multipath coded forwarding than that under multipath forwarding. Fig. 3(b) plots the results when the routing pipe radius, R, is increased to 2. We observe that the performance of both multipath forwarding and multipath coded forwarding improves significantly compared to that when $R = 1$. Furthermore, multipath coded forwarding outperforms multipath forwarding for all the link loss probabilities we examined. This demonstrates the importance of carefully coupling transmission schemes and the parameters in the routing protocols to achieve a satisfactory error-recovery rate. Fig. 3(c) plots the total number of transmissions for multipath forwarding and multipath coded forwarding. We observe that the superior error recovery of multipath coded forwarding does not come at the price of much higher amount of traffic. For instance, for $p = 0.2, R = 2$, the fraction of delivered packets improves from 0.78 to 0.95 by using multipath coded forwarding while the total number of transmission only increased by 14%.

We now examine the impact of the routing pipe radius on the performance of multipath coded forwarding. The results are shown in Fig. 4. From Fig. 4(a), we observe a diminishing gain from increasing the radius: the performance improvement is dramatic when the radius increases from 1 to 2 and becomes less dramatic afterwards. This diminishing gain demonstrates that network coding does not require too many paths to achieve its performance gain. Fig. 4(b) shows that increasing the radius from 1 to 2 does not lead to significantly more transmissions.

3.2 Source-encoding setting

We now look at the setting where the source linearly encodes the k packets in a generation into k' ($k' \geq k$) packets and then send the encoded packets to the destination. A relay receiving m incoming packets in the same generation will encode them into m' outgoing packets, $m' = \min(k', m)$. That is, a relay does not inject more packets into the network than the amount injected by the source.

We expect the performance in this setting to be better than that in the source-forwarding setting. This is because, when source performs network coding, each outgoing packet from the source contains information of all packets in the same generation. Hence the effect of losing one packet in the first hop is not as detrimental as in the source-forwarding setting. We compare the performance of these two settings in Fig. 5, where for each generation (of 3 packets), the maximum number of packets sent on a link (by a source or relay in source-encoding and by a relay in source-forwarding) is varied from 3 to 6 packets. We observe that, as expected, allowing more packets from the source and the relays leads to better error-recovery. When the routing pipe radius is $R = 2$, the improvement is especially significant when allowing slightly more than 3 packets, i.e., 4 packets (at the cost of slightly more transmissions as shown in Fig. 5(b)). We also observe that source-encoding indeed outperforms source-forwarding for all the cases except when allowing only 3 packets at the source (where their performances are similar).

4. CONCLUSIONS AND FUTURE WORK

In this paper, we designed a network coding scheme for underwater sensor networks and evaluated its performance through simulation. Our initial results indicate that network coding is indeed a promising technique for efficient error-recovery in underwater sensor networks. Our results also demonstrate the importance to couple network coding and routing carefully as well as the gains from encoding at the source.

As future work, we are pursuing in the following directions: (1) evaluating the performance of our coding scheme in more general settings, including heterogenous link loss probabilities, less regular topologies, multiple source-destination pairs, limited relay buffer sizes, and different generation sizes. We also plan to look at the scenarios where packets are generated following a certain process (e.g., generated periodically); (2) designing network coding schemes for transmission from multiple sources to a single receiver.

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