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# Efficient error recovery with network coding in underwater sensor networks ☆

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ABSTRACT

Before the wide deployment of underwater sensor networks becomes a reality, one challenge to be met is efficient error recovery in the presence of high error probability, long propagation delays and low acoustic bandwidth. We believe that network coding is a promising technique for this purpose due to Eq. (1) the computational capability of underwater sensor nodes, and Eq. (2) the broadcast nature of acoustic channels. In this paper, we propose an efficient error-recovery scheme that carefully couples network coding and multiple paths. Through an analytical study, we provide guidance on how to choose parameters in our scheme and demonstrate that the scheme is efficient in both error recovery and energy consumption. We evaluate the performance of this proposed scheme through simulation, and the simulation confirms the results from the analytical study.



## 1. Introduction

Over 70% of the surface of the earth is covered by water. Despite years of research, many critical underwater applications, such as oceanographic data collection, pollution monitoring, tactical surveillance applications, remain quite limited. The studies of [2–6] survey fundamental constraints, potential applications, challenges and future research directions in underwater environments. They point out that one ideal vehicle for these aquatic applications is underwater sensor network (UWSN) [4]. However, the characteristics of UWSNs, such as low bandwidth, long propagation delays and high error probability, are significantly different from those in terrestrial sensor networks. These unique characteristics pose a range of challenges [2–6]. One such challenge is efficient error recovery when using underwater acoustic channels. Under such severe network conditions, commonly used error-recovery techniques such as automatic repeat reQuest (ARQ) and forward error correction (FEC) become unsuitable (detailed in Section 2).

In a prior study, we demonstrate that network coding is a promising technique for error recovery in UWSNs [7]. The main idea of network coding [8,9] is that, instead of simply forwarding a packet, a node may encode several incoming packets into one or multiple outgoing packets. Network coding is suitable for UWSNs because Eq. (1) underwater sensor nodes are usually larger than land-based sensors and possess more computational capabilities [10]; and Eq. (2) the broadcast property of acoustic channels naturally renders multiple highly interleaved paths from a source to a sink. The computational power at the sensor nodes coupled with the multiple paths provides ample opportunity to apply network coding.

We now illustrate the benefits of network coding using a simple example in Fig. 1. Fig. 1a illustrates the result when using network coding. A source generates packets $A$, $B$ and $C$, encodes these packets into $X_1$, $X_2$ and $X_3$, and then sends them to a sink.[1] These packets will reach relays

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[1] A simple form of coding is that the encoded packets are copies of the original packets, e.g., $X_1 = A$, $X_2 = B$ and $X_3 = C$.

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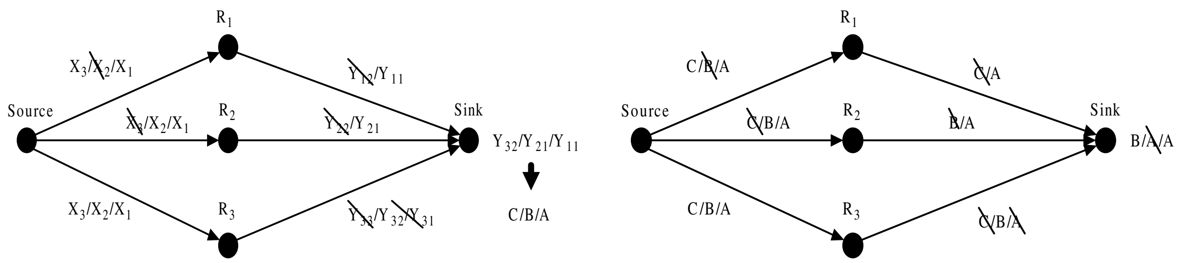


(a) Using network coding. (b) Not using network coding.

**Fig. 1.** An example illustrating the benefits of using network coding in underwater sensor networks. A packet crossed out means that the packet is lost.

$R_1$, $R_2$ and $R_3$ simultaneously because of the broadcast property of the acoustic channel. Relay $R_1$ receives packets $X_1$ and $X_3$ successfully and encodes them into packets $Y_{11}$ and $Y_{12}$. Similarly, relay $R_2$ encodes its incoming packets into packets $Y_{21}, Y_{22}$, and relay $R_3$ encodes its incoming packets into $Y_{31}, Y_{32}, Y_{33}$. The relays then forward the encoded packets to the sink. The sink receives three encoded packets $Y_{11}$, $Y_{21}$, and $Y_{32}$. When using a proper network coding scheme (e.g., random linear coding [11]), the sink can recover the three original packets with high probability. Fig. 1b illustrates the result when the relays simply forward the incoming packets without using network coding and discard duplicated packets. In this case, the sink only receives two distinct original packets.

In this paper, extending our preliminary work [7], we provide an in-depth study on using network coding in UWSNs. Our main contributions are as follows: Eq. (1) we propose an error-recovery scheme using network coding, and analytically study the performance of our scheme along with several other error-recovery schemes. Our analysis provides guidance on how to choose parameters in the proposed scheme and demonstrates that, of all schemes, our scheme is the most efficient in error recovery and energy consumption, and Eq. (2) we evaluate the performance of our scheme through simulation, and the simulation confirms the results from the analytical study.

The rest of the paper is organized as follows. We first discuss related work in Section 2. We then present the problem description and the propose an error-recovery scheme based on network coding in Sections 3 and 4 respectively. Section 5 analytically studies the performance of our scheme along with several other schemes. We next describe our evaluation methodology and evaluate the schemes through simulation in Section 6. Finally, Section 7 concludes the paper and presents future work.

## 2. Related work

Automatic repeat reQuest (ARQ) [12] and forward error correction (FEC) [13,14] are two conventional methods for error recovery. They, however, both have severe drawbacks when applied to UWSNs. ARQ-based schemes require the receiver to detect lost packets and then request the sender to retransmit packets. This may lead to a long delay before a packet is delivered successfully due to the slow propagation through acoustic channels. FEC-based schemes can be classified as end-to-end FEC and hop-by-hop FEC (e.g., [14]). These schemes proactively add redundant packets, so that the receiver (for hop-by-hop case) or the sink (for the end-to-end case) may successfully recover original packets, and hence eliminate the need for packet retransmissions. But the amount of redundancy needs to be sufficient to recover errors while conserving the limited battery power of sensor nodes. Determining the right amount of redundancy is, however, a challenging task due to the difficulty to obtain accurate error-rate estimates [4].

Due to the drawbacks of ARQ-based and FEC-based schemes, researchers have proposed other schemes to improve the robustness of sensor networks [10,15,16]. One scheme is multi-path forwarding [10,15], which uses redundant packets through multiple paths to improve packet delivery ratio. However, as we have seen in Fig. 1, multi-path forwarding alone is not sufficient because duplicated packets, which will be discarded directly, consume energy but do not provide any innovative information. Another scheme [16] uses multiple virtual sinks to provide error resilience: a source forwards packets to multiple virtual sinks using acoustic communication, then the virtual sinks forward the packets to the final destination using high-bandwidth wireless radio communication. This scheme requires a specialized delivery infrastructure. Our scheme applies to the single sink architecture and uses a collaborative coding scheme to fully utilize the scare resources in UWSNs.

Network coding is first proposed by Ahlswede et al. [8]. They use network coding to achieve the broadcast capacity of a multicast tree, which cannot be achieved by simply copying and forwarding packets. Afterwards, Li et al. prove that linear network coding is sufficient for the encoding functions [17]. Koetter et al. show how to find the coefficients of the linear coding and decoding functions [18]. Fragouli et al. present an instant primer on network coding in [9].

We apply network coding to UWSNs for reliable data transfer [1,7], and demonstrate that coupling network coding and multiple paths improves data delivery ratio and provides high energy efficiency. Lucani et al. propose a network-coding based method that relies on the implicit acknowledgement of previously transmitted packets to improve power consumption performance in UWSNs [19]. They consider a concatenated relay network and focus on the time to complete the transmissions of a given