Efficient Error Recovery Using Network Coding in Underwater Sensor Networks *

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Abstract. Before the wide deployment of underwater sensor networks becomes a reality, one of the challenges that needs to be resolved is efficient error recovery in the presence of high error rates, node mobility and long propagation delays. In this paper, we propose an efficient error-recovery scheme that carefully couples network coding and multipath routing. Through an analytical study, we provide guidance on how to choose parameters in our scheme and demonstrate that our scheme is efficient in both error recovery and energy consumption. We evaluate the performance of our scheme using simulation and our simulation confirms the results from the analytical study.

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 [1–3]. One such challenge is efficient error recovery in the presence of high error rates, node mobility and long propagation delays (caused by fast fading acoustic channel, water currents and 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. FEC-based schemes proactively add redundant packets to eliminate retransmission from the source. The FEC can be applied on an end-to-end or hop-by-hop basis (as in [4]). However, in either case, the proper amount of redundancy is hard to decide due to the difficulty of obtaining accurate error-rate estimates [3].

In our prior study [5], we demonstrate that network coding is a promising technique for error recovery in underwater sensor networks. The main idea of network coding [6, 7] is that, instead of simply forwarding a packet, a node may code several incoming packets into one or multiple outgoing packets. Network coding is suitable for underwater sensor networks because (1) underwater sensor nodes are usually larger than land-based sensors and posses more computational capabilities [8]; (2) the broadcast property of acoustic channels naturally renders multiple highly interleaved routes from

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a source to a sink. The computational power at the sensor nodes coupled with the multiple routes provides ample opportunity to apply network coding.

In this paper, building upon our preliminary work [5], we provide an in-depth study on using network coding in underwater sensor networks. Our main contributions are as follows. First, we propose an error-recovery scheme that carefully couples network coding and multipath routing. Second, we analytically study the performance of this scheme along with several other error-recovery schemes. Our analysis provides guidance on how to choose parameters in our scheme and demonstrates that, among the multiple schemes, our scheme is most efficient in terms of error recovery and energy consumption. Last, we evaluate the performance of our scheme using simulation and the simulation confirms the results from the analytical study.

As related work, multipath routing schemes have been proposed for error resilience in sensor networks (e.g., [9, 8]). Our scheme carefully combines network coding and multipath routing and provides much better error recovery than using multipath routing alone (see Sections 4 and 5). The study of [10] provides error resilience using multiple virtual sinks: a source forwards packets to multiple high-bandwidth virtual sinks, which then forward the packets to the final destination. This scheme requires a specialized delivery infrastructure while our scheme does not have such a requirement.

The rest of the paper is organized as follows. Section 2 describes the problem setting. Section 3 describes our error-recovery scheme based on network coding. Sections 4 and 5 study the performance of our scheme along with several other schemes using analysis and simulation respectively. Finally, Section 6 concludes the paper and presents future work.

2 Problem Setting

We now describe the problem setting. Consider a source-sink pair in an underwater sensor network. The path (or multipath) from the source to the sink is determined by a single-path (or multipath) routing algorithm. We refer to the intermediate nodes on the path(s) as *relays*.

We consider several error-recovery schemes including single-path forwarding, end-to-end FEC, hop-by-hop FEC, multipath forwarding and network coding. In single-path and multipath forwarding, packets are simply forwarded, without any coding. Single-path forwarding is a baseline scheme since it does not exploit any extra mechanism for error recovery. Multipath forwarding recovers error through redundant packets over the multiple paths (a relay does not forward duplicate packets). FEC-based schemes use a single path from the source to the sink: end-to-end FEC encodes packets at the source and decodes them at the the sink; in hop-by-hop FEC, each relay on the path decodes incoming packets, encodes the recovered packets, and then forwards them to the next hop. Network coding requires multiple paths from the source to the sink; a node encodes incoming packets into one or multiple outgoing packets, as to be described in detail in Section 3.

A packet successfully received (under single or multipath forwarding) or recovered (under FEC or network coding) is referred to as a *successfully delivered packet*. Since efficient error-recovery schemes for underwater sensor networks must achieve high error-recovery rate and conserve sensor node energy simultaneously, we consider the following two metrics. The first metric is the number of successfully delivered packets over the total number packets from the source, referred to as *successful delivery ratio*, denoted as R. The second metric is the total number of transmissions from the source to the sink (including transmissions from the source and relays) normalized by the successful delivery ratio. Since the number of transmissions roughly corresponds to the amount of energy consumed in the network, we refer to this metric as *normalized energy consumption*, denoted as T. This metric represents the average number of transmissions required for a successfully delivered packet.

We next describe our network coding scheme for underwater sensor networks and then evaluate the various schemes using analysis and simulation.

3 Using Network Coding in Underwater Sensor Networks

We now describe our error-recovery scheme based on network coding. This scheme carefully couples network coding and multipath routing to achieve a good balance between error recovery and energy consumption. In the following, we first describe how to apply network coding (we use random linear coding [11] due to its simplicity) given a set of paths from a source to a sink. We then describe how to adapt the multiple paths or the amount of redundancy to improve the efficiency of network coding.

3.1 Network coding scheme

Packets from the source are divided into generations, each generation contains K packets. The source linearly combines K packets in a generation using randomly generated coefficients. More specifically, let $X_1, \ldots, X_K$ denote the K packets in a generation. The source linearly combines these K packets to compute 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_{2^q}. The set of coefficients $(g_{i1}, \ldots, g_{iK})$ is referred as the *encoding vector* for Y_i [7] and are carried in a packet as overhead. We choose $K' \geq K$ since adding a small amount of redundancy at the source (e.g., $K' = K + 2$) reduces the impact of packet loss on the first hop (which cannot be recovered at later hops) and improves error recovery at the sink [5].

A relay in forwarding paths stores incoming packets from different routes in a local buffer for a certain period of time, then linearly combines the buffered packets belonging to the same generation. 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, $i = 1, \ldots, M$. Since transmitting dependent packets is not useful for decoding at the sink, relay r computes M' outgoing packets, where M' is the rank of the coefficient matrix (f_{ij}), $i = 1, \ldots, M$, $j = 1, \ldots, K$. Therefore, $M' \leq \min(M, K)$. Let $Y_1^r, \ldots, Y_{M'}^r$ denote the outgoing packets, $Y_i^r = \sum_{j=1}^{M} h_{ij}^r X_j^r$, where h_{ij} is picked randomly from the finite field F_{2^q}. Let $(g_{i1}^r, \ldots, g_{iK}^r)$ denote the encoding vector of Y_i^r, $i = 1, \ldots, M'$. Then $g_{ij}^r = \sum_{l=1}^{M} h_{il}^r f_{lj}$.

When the sink receives K packets with linearly independent encoding vectors, it recovers the original packets by matrix inversion [7]. The complexity is $O(K^3)$.

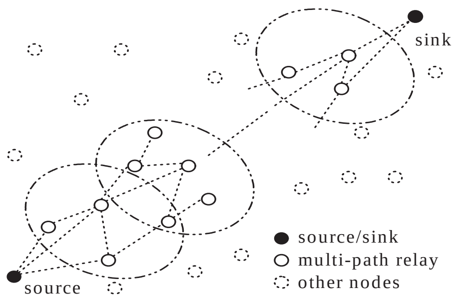


Fig. 1. Illustration of transmitting a packet along multiple paths from the source to the sink. Nodes in a dashed circle form a relay set.

3.2 Path or redundancy adaption for network coding

The efficiency of network coding relies on the quality of the underlying paths determined by a multipath routing algorithm. We next describe a multipath property under which network coding is efficient (in terms of both error recovery and energy consumption). Fig. 1 illustrates the process of transmitting a packet along a multipath. The source broadcasts the packet to its downstream neighbors (nodes within its transmission range and in the forwarding paths), referred to as a *relay set*. Nodes in the relay set further forward the packet to their neighbors, forming another relay set. Intuitively, a multipath suitable for network coding should contain a similar number of nodes in each relay set. This is because, a relay set with too few nodes may not provide sufficient redundancy; a relay set with too many nodes wastes energy to provide more redundancy than what is necessary for error recovery.

We develop two schemes to adjust the multipath or the amount of redundancy to improve the efficiency of network coding. In both schemes, a node uses the number of its downstream neighbors to approximate the size of its downstream relay set. This is because the former can be easily estimated through localization service (e.g., [12]) and localized communication between a node and its neighbors while the latter is difficult to estimate.

The first scheme requires that sensor nodes have multiple levels of transmission power [13]. A node selects a transmission power so that the estimated number of downstream neighbors is between N_l and N_u, where N_l and N_u are lower and upper thresholds respectively. We refer to this scheme as *transmission-range adaption*. In the second scheme, each node has a fixed transmission range and a node adapts the amount of redundancy that it injects to the network. More specifically, a node with less than a N_l' downstream neighbors encodes more outgoing packets to increase the amount of redundancy. Similarly, a node with more than N_u' downstream neighbors encodes less outgoing packets to reduce the amount of redundancy (we only do this when the coefficient matrix at the node has a full rank of K). We refer to this scheme as *redundancy adaption*.

Our analytical results in the next section provide guidance on how to choose parameters for the above two adaption schemes. Note that both schemes only require localized information and hence are easy to deploy. Furthermore, they can be applied to mobile underwater sensor networks when coupled with a multipath routing scheme that supports mobility (e.g., [8]).

4 Analytical Study

We now analytically study the performance of the various error-recovery schemes in Section 2. Our goal is two-fold: (1) analytically compare the efficiency of the various schemes; (2) provide guidance on how to choose parameters in network coding. In the interest of space, we only present the results for multi-path forwarding and network coding; the results for other schemes can be found in [14].

Multi-path forwarding and network coding use the same multipath from the source to the sink. Assume that there are H relay sets from the source to the sink, indexed them from 1 to H (see Fig. 1). The sink is in the H-th relay set. Let N_i be the number of relays in the i-th relay set. For simplicity, we assume that the relay sets do not intersect. Furthermore, a node in a relay set can receive from all nodes in the previous relay set. Last, a node only uses packets forwarded from its previous relay set (i.e., packets received from nodes in the same relay set are discarded). For both schemes, we derive the normalized energy consumption, T, from the successful delivery ratio, R, as follows. Consider an arbitrary packet (regardless of being successfully delivered or not), let T_i denote the average number of times that it is transmitted from the nodes in the previous relay set (or the source) to those in the i-th relay set. Then

$$T = \frac{\sum_{i=1}^{H} T_i}{R} \tag{1}$$

We assume that the acoustic channels have the bit error rate of p_b. Let p be the probability that a packet has bit error. Then $p = 1-(1-p_b)^L$ for independent bit errors and a packet size of L bits. We next present the analysis for multipath forwarding and network coding.

4.1 Analysis of Multipath Forwarding

Consider an arbitrary packet P. Let α_i be the probability that a node in the i-th relay set receives packet P. Let $\alpha_{i,n}$ be the probability that n nodes in the i-th relay set receive packet P, $n = 0, \ldots, N_i$. Assume that packet losses are independent. Then

$$\alpha_i = \begin{cases} 1-p & i = 1 \\ \sum_{n=0}^{N_{i-1}} \alpha_{i-1,n}(1-p^n), & 2 \leq i \leq H \end{cases} \tag{2}$$

This is because, for a node in the first relay set, the probability that it receives packet P from the source is $1-p$; when $i \geq 2$, a node in the i-th relay set receives packet P when it receives at least one copy of this packet from the $(i-1)$-th relay set. Assume that packet transmissions to nodes in a relay set are independent. Then

$$\alpha_{i,n} = \binom{N_i}{n} \alpha_i^n (1-\alpha_i)^{N_i - n}, n = 0, \ldots, N_i \quad (3)$$

Since packet P is an arbitrary packet and the sink is in the H-th set, we have $R = \alpha_H$. The above results indicate that α_H can be obtained in the following manner. We first obtain $\alpha_{1,n}$ from α_1 (of value $1-p$), and then obtain α_2 using $\alpha_{1,n}$. This process continues until eventually α_H is obtained.

Since a node forwards packet P at most once, we have

$$T_i = \begin{cases} 1, & i = 1 \\ \alpha_{i-1} N_{i-1}, & 2 \le i \le H \end{cases} \quad (4)$$

After obtaining R and T_i, we calculate the normalized energy consumption T from (1).

4.2 Analysis of Network Coding

Consider an arbitrary generation of K packets. Under linear random coding, when a sink receives at least K packets in the generation, the probability that it can recover the K original packets is high for a sufficiently large finite field [11]. Therefore, for simplicity, we assume that the sink recovers the K original packets as long as it receives at least K packets in the generation. We do not differentiate nodes in the same relay set. Let $\beta_{i,k}$ be the probability that a node in the i-th relay set receives k packets (when $0 \le k < K$) or at least k packets (when $k = K$) from all nodes in the previous relay set, $1 \le i \le H$. Since the sink is in the H-th relay set and the generation is arbitrary, we have $R = \beta_{H,K}$.

We next derive $\beta_{i,k}$, $1 \le i \le H$, $0 \le k \le K$. The nodes in the first relay set receive packets from the source. Therefore

$$\beta_{1,k} = \begin{cases} \binom{K'}{k}(1-p)^k p^{K'-k}, & 0 \le k < K \\ 1 - \sum_{j=0}^{K-1} \beta_{1,j} & k = K \end{cases} \quad (5)$$

where $K' \ge K$ is the number of encoded packets from the source.

For $i \ge 1$, $0 \le k < K$, we obtain $\beta_{i+1,k}$ as follows. We index the nodes in the i-th relay from 1 to N_i. Let $\gamma_{i,j,k}$ denote the probability that a node in the i-th relay set receives k packets from the j-th node in the previous relay set, $1 \le i \le H$, $1 \le j \le N_{i-1}$, $0 \le k < K$. Since each relay transmits no more than K packets, we have

$$\gamma_{i,j,k} = \sum_{n=k}^{K} \beta_{i-1,k} \binom{n}{k} (1-p)^k p^{n-k} \quad (6)$$

For a node in the $(i+1)$-th set, let k_j be the number of packets that it receives from the j-th node in the previous relay set. To obtain $\beta_{i+1,k}$, we need to consider all combinations of k_j's such that $\sum_{j=1}^{N_i} k_j = k$, $k_j = 0, \ldots, k$. That is,

$$\beta_{i+1,k} = \sum_{k_j=0,\ldots,k \text{ s.t. } \sum_{j=1}^{N_i} k_j = k} \prod_{j=1}^{N_i} \gamma_{i+1,j,k_j} \tag{7}$$

For a small generation size K, the above quantity is easy to compute. We use small K (e.g., $K = 3$) since our study [5] indicates that it is sufficient to achieve good performance using small K (also confirmed by simulation in the settings of Section 5).

We obtain $\beta_{i+1,K}$ from $\beta_{i+1,k}$, $0 \leq k < K$ as

$$\beta_{i+1,K} = 1 - \sum_{k=0}^{K-1} \beta_{i+1,k} \tag{8}$$

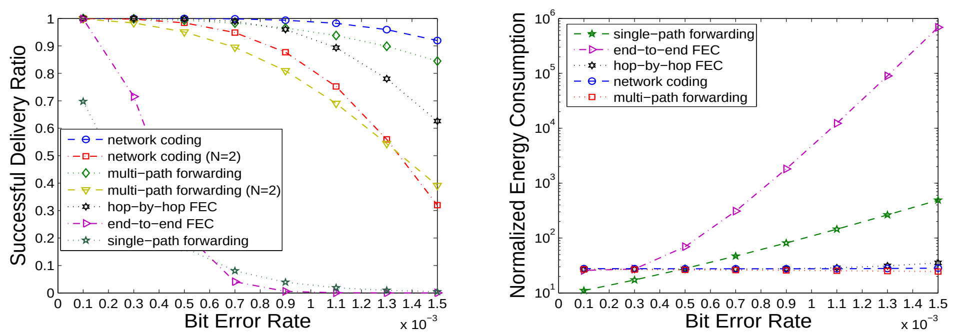
From the above, we calculate $R = \beta_{H,K}$ as follows. We first obtain $\beta_{1,k}$, which is used to compute $\gamma_{2,j,n}$ and $\beta_{2,k}$, $0 \leq k \leq K$. This process continues until eventually $\beta_{H,K}$ is obtained.

Since a relay transmits no more than K packets, we have

$$T_i = \begin{cases} K'/K, & i = 1 \\ \frac{N_{i-1}}{K} \sum_{k=0}^{K} k\beta_{i-1,k}, & 2 \leq i \leq H \end{cases} \tag{9}$$

After obtaining R and T_i, we calculate the normalized energy consumption T from (1).

4.3 Numerical Results



(a) Successful delivery ratio. (b) Normalized energy consumption.

Fig. 2. Numerical results, $H = 9$, $N = 3$ unless otherwise specified.

We next compare the various schemes based on our analytical results. The bit error rate is in the range of 10^{-4} to 1.5×10^{-3} to account for potential high loss rate in underwater sensor network (e.g., due to fast channel fading). For network coding, a generation contains 3 packets (e.g., $K = 3$). The source transmits $K' = 5$ packets.

For multipath forwarding and network coding, we set the number of relay sets, H, to 7 or 9, and assume all relay sets contain the same number of nodes, i.e., $N_i = N$, $i = 1, \ldots, H$. Similarly, for single-path forwarding and FEC, we set the number of hops from the source to the sink to 7 or 9. For FEC, each block contains 3 packets (same as the generation size in network coding) and the amount of redundancy is $3N - 3$ since a relay set contains N nodes in multipath forwarding and network coding.

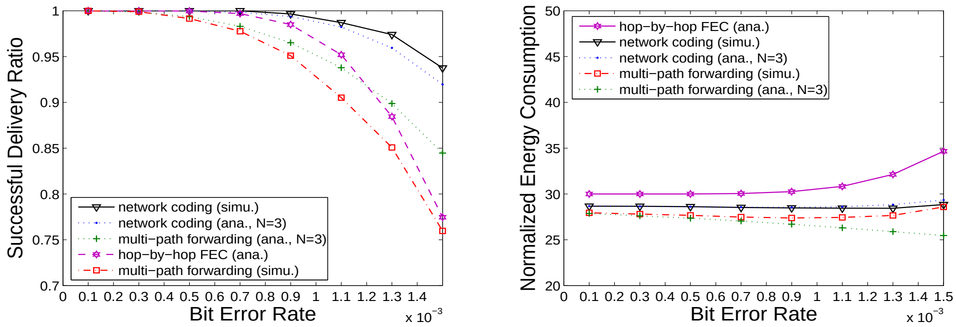
Fig. 2 plots the successful delivery ratio and normalized energy consumption for various schemes when $H = 9$. We observe that network coding outperforms the other schemes: it achieves the highest successful delivery ratio and the lowest normalized energy consumption for the range of bit error rates when $N = 3$ (i.e., each relay set contains 3 nodes). Furthermore, network coding achieves similar performance when $H = 7$ (not plotted), indicating that it is insensitive to the length of the path (network size). We also observe that when the number of nodes in each relay set, N, is decreased from 3 to 2, the successful delivery ratio of network coding drops sharply. Based on the above results, we set $N_l = N_l' = 3$ in our simulation 5.

From Fig. 2, we also observe that multipath forwarding achieves a similar normalized energy consumption and a lower successful delivery ratio than network coding for the same value of N. The successful delivery ratio under hop-by-hop FEC is sensitive to both the bit error rate and the number of hops on the path (network size), indicating that the amount of redundancy needs to be carefully selected according to these two parameters. The successful delivery ratio under single-path forwarding and end-to-end FEC decreases significantly as the bit error rate increases, indicating that they are not suitable for high error-rate underwater sensor networks.

5 Simulation Study

We now evaluate the performance of the various error-recovery schemes using simulation. The underwater sensor network is deployed in a cubic target area of $1km \times 1km \times 1km$. The source and sink are deployed respectively at bottom corner and surface corner, on the diagonal of the cube. The MAC layer supports broadcasting. The routes from the source to the sink is determined by Vector-based Forwarding (VBF) [8]. In VBF, a routing pipe is a pipe centered around the vector from the source to the sink. Nodes inside the routing pipe are responsible for routing packets from the source to the sink; nodes outside the routing pipe simply discard all incoming packets. Each packet is 50 bytes. For network coding, each generation contains $K = 3$ packets; the source outputs $K' = 5$ packets for each generation and each relay outputs no more than 3 packets. We choose a finite field of F_{2^8} [11], leading to packets of 53 bytes (including 3-byte encoding vector). A relay has a memory to store 10 packets for each generation; packets transmitted from the node are removed from the memory.

We look at two types of sensor deployment: *grid random deployment* and *uniform random deployment*. In grid random deployment, the target area is divided into grids; a number of nodes are randomly deployed in each grid. In uniform random deployment, nodes are uniformly randomly deployed in the area. Grid random deployment covers the area more evenly than uniform random deployment while uniform random deployment is easier to deploy.



(a) Successful delivery ratio. (b) Normalized energy consumption.

Fig. 3. Simulation results under grid random deployment.

The comparative results of the various schemes from simulation are consistent with those from analytical study. We focus on the performance of network coding and multipath forwarding in the following.

5.1 Performance under Grid Random Deployment

In grid random deployment, the target area is divided into 125 grids, each grid is $200m \times 200m \times 200m$. Each grid contains 2 nodes, randomly distributed in the grid. Based on the analytical results in Section 4, we set the transmission power and pipe radius of a node to cover 3 to 4 downstream neighbors (with an average of 3.1). This is achieved when each node uses a transmission range of 300 m, which can be supported by existing acoustic modems like WHOI Micro-modem [15], and a pipe radius of 150 m.

Figures 3 (a) and (b) plot the successful delivery ratio and normalized energy consumption for network coding and multipath forwarding. The confidence intervals (from 20 simulation runs) are tight and hence omitted. We also plot the analytical results when $N = 3$ (i.e., each relay set contains 3 nodes). For network coding, we observe that the simulation results are very close to those from the analysis, indicating that the analysis provides a good approximation and guidance on choosing parameters in network coding. For multipath forwarding, the analytical results are slightly (no more than 8%) higher than those from the simulation. This might be because we assume a node can hear from all nodes from its previous relay set in the analysis, which provides an overestimate of the successful delivery ratio. We observe that network coding provides significantly better error recoveries than multipath forwarding for high bit error rates. The normalized energy consumption under network coding is slightly higher than that under multipath forwarding because the source adds redundancy and more packets are forwarded at a relay in network coding (a relay discards duplicate packets in multipath forwarding).

For the sake of comparison, we also plot the analytical result under hop-by-hop FEC in Fig. 3. When using this scheme, the number of hops (on the single path) from the source to the sink is 9, and a block contains 3 packets (to be consistent with the generation size in network coding). Each blocks adds $\lceil 28/9 * 3 - 3 \rceil = 7$ redundant packets since the routing pipe used in network coding and multipath forwarding contains 28 nodes. Note that, although we purposely add a higher amount of redundancy for hop-by-hop FEC, it still achieves much lower successful delivery ratio than network coding for relatively high bit error rates.

We now demonstrate that it is indeed important for a node to have 3 to 4 downstream neighbors for efficient network coding, as indicated by the analytical results. For this purpose, we either fix the transmission range to 300 m and vary the pipe radius or fix the pipe radius to 150 m and vary the transmission range. The results are plotted in Figures 4(a) and (b) respectively, where the bit error rate is 1.5×10^{-3}. In both cases, we observe that a good balance between error recovery and energy consumption is achieved when the transmission range is 300 m and the pipe radius is 150 m (i.e., when a node has 3 to 4 downstream neighbors).

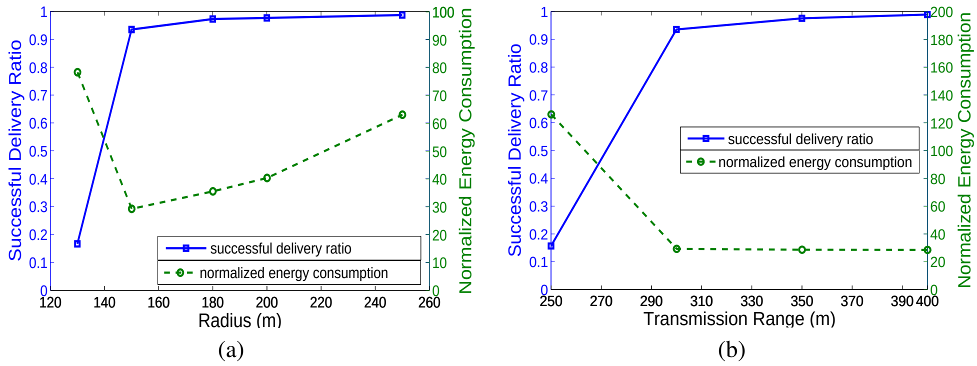


Fig. 4. Successful delivery ratio and normalized energy consumption under grid random deployment: (a) Transmission range is 300 m, (b) Pipe radius is 150 m.

5.2 Performance under Uniform Random Deployment

We now present the results under uniform random deployment. Under this type of deployment, we find that using the same transmission range and pipe radius for all the nodes cannot ensure 3 to 4 downstream neighbors for each node. We therefore allow a node to adjust its transmission range or the amount of redundancy that it injects into the network.

We first present the result under transmission-range adaptation. The pipe radius is set to 150 m. A node set its transmission range to have 3 to 4 downstream neighbors (with an average of 3.3). The resulting transmission ranges are from 100 to 400 m for all the nodes. Fig. 5 plots the successful delivery ratio under network coding. We observe that transmission-range adaption achieves a similar successful delivery ratio as that from the analytical result using $N = 3$. This indicates that transmission-range adaption is effective for error recovery. For comparison, we obtain the results when all

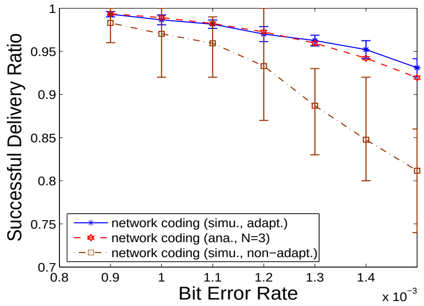


Fig. 5. Transmission-range adaption in uniform random deployment.

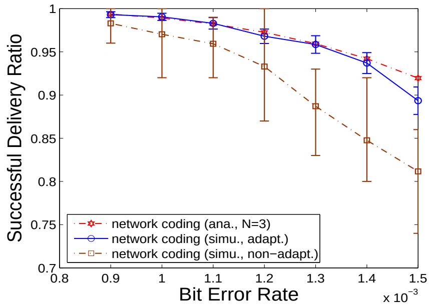


Fig. 6. Redundancy adaption in uniform random deployment.

nodes uses a transmission range of 300 m. We observe that it achieves significantly lower successful delivery ratio (see Fig. 5) and higher normalized energy consumption (not plotted) than those under transmission-range adaption.

We next present the results when all nodes uses the same transmission range of 300 m and adjusts the amount of redundancy according to the number of its downstream neighbors. In Fig. 6, a node adds one more outgoing packet when it has less than 3 downstream neighbors and removes an outgoing packet when it has more than 6 downstream neighbors. We observe that this adaption achieves a similar successful delivery ratio as that from the analysis using $N = 3$ with only slightly higher normalized energy consumption (not plotted). The above results demonstrate that adjusting redundancy is also helpful for efficient error recovery under network coding.

6 Conclusions and Future Work

In this paper, we first proposed an efficient error-recovery scheme that carefully couples network coding and multipath routing for underwater sensor networks. We analytically studied the performance of this scheme along with several other error-recovery schemes. Our analysis provided guidance on how to choose parameters in our scheme and demonstrated that our scheme is the most efficient among the multiple schemes. Finally, we evaluated the performance of our scheme using simulation, which confirmed the analytical study that our scheme is efficient in both error recovery and energy consumption.

As future work, we are pursuing in three directions: (1) analyzing traffic congestion and delays when using network coding; (2) using network coding in multicast applications in underwater sensor networks, e.g., command distribution or software update from one source to all other nodes; (3) using network coding in the architecture with multiple virtual sinks.

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