

Efficient Error Recovery with Network Coding in Underwater Sensor Networks

Zheng Guo, Bing Wang and Jun-Hong Cui

{*guozheng, bing, jcui*}@*enr.uconn.edu*

UConn CSE Technical Report: UbiNet-TR06-05

Last Update: December 2006

Abstract

Wireless sensor networks usually suffer higher error probability and loss rate than wired networks, especially in Underwater Sensor Networks (UWSN). We have noticed that network coding could bring us benefits in both wired and wireless networks, e.g., increasing the throughput. Because of the special conditions of UWSN, we find applying network coding and multi-path routing in UWSN could provide efficient robustness. This is based on the natural physical broadcast property in shared media and multiple interleaved paths provided. We compare our approach with ordinary single path forwarding, multi path, end-to-end FEC and even hop-by-hop FEC, our approach achieves a better efficient error recovery.

I. 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 possess more computational capabilities [4]. Furthermore, the broadcast property of acoustic channels naturally renders multiple routes from a

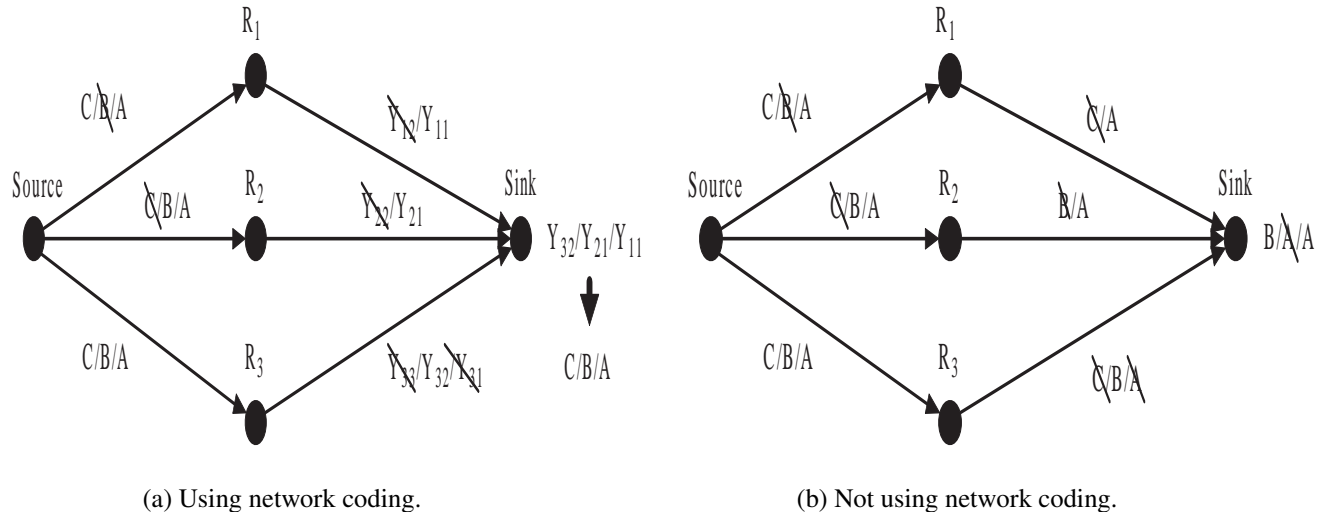


Fig. 1. An example illustrating the benefits of using network coding in underwater sensor networks.

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.

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 output 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 [5]), 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.

II. RELATED WORK

For the error recovery purpose, the commonly used methods are ARQ, FEC and multi-path routing. ARQ is not practical because of the long propagation delay in under water sensor network; Both end-to-end FEC and hop-by-hop FEC are difficult to decide the proper redundancy according to the fast channel fading. Later multi-path coded forwarding is proposed to improve the robustness. However, as we see in 1, only use multiple path could not fully utilize the network resource. Our scheme carefully combines network coding and multi-path routing and provides

much better error recovery than using multi-path routing alone. The study of [6] 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.

In this paper, building upon our preliminary work [7], 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 our 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.

III. 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. 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. In network coding, a node codes incoming packets into one or multiple outgoing packets, as to be described in detail in Section IV.

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.

IV. USING NETWORK CODING IN UNDERWATER SENSOR NETWORKS

We now describe our scheme to apply network coding in underwater sensor networks. To achieve a good balance between error recovery and energy consumption at the sensor nodes, our scheme carefully couples network coding and multipath routing. In the following, we first describe how to apply network coding (we use random linear coding [5] 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.

A. 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, \dots, X_K denote the K packets in a generation. The source linearly combines these K packets to compute K' outgoing packets, denoted as $Y_1, Y_2, \dots, Y_{K'}$ 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}, \dots, g_{iK}) is referred as the *encoding vector* for Y_i [8] 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 [7].

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, \dots, X_M^r . Let (f_{i1}, \dots, f_{iK}) denote the encoding vector carried by X_i^r , $i = 1, \dots, M$. 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}) , $i = 1, \dots, M$, $j = 1, \dots, K$. Therefore, $M' \leq \min(M, K)$. Let $Y_1^r, \dots, Y_{M'}^r$ denote the outgoing packets, $Y_i^r = \sum_{j=1}^M h_{ij} X_j^r$, where h_{ij} is picked randomly from the finite field F_{2^q} . Let $(g_{i1}^r, \dots, g_{iK}^r)$ denote the encoding vector of Y_i^r , $i = 1, \dots, M'$. 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 [8]. The complexity is $O(K^3)$.

B. Path or redundancy adaptation 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 property of a multipath under which network coding is efficient (in terms of both error recovery and energy consumption). Fig. 2 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),

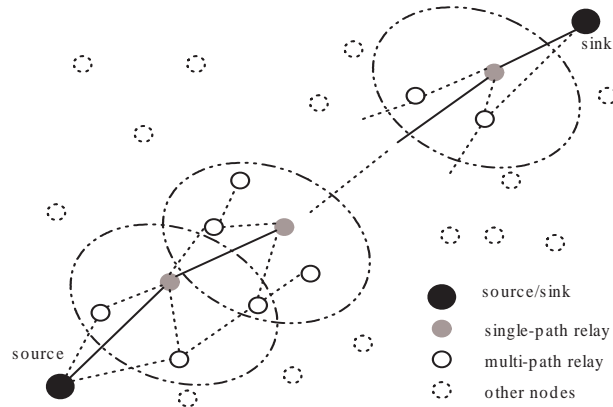


Fig. 2. Illustration of routing (nodes in a dashed circle form a relay set).

referred to as a *relay set*. Nodes in the relay set further forward the packet to their neighbors, forming another relay set. The solid line is the default single path. 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., [9]) and localized communication between a node and its neighbors while the latter is difficult to estimate.

The first scheme requires that sensor nodes are equipped with multiple levels of transmission power [10]. 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 provide guidance on how to select N_l and N_u using our analytical results in Section V. This scheme is referred to as *transmission-range adaptation*.

The second scheme does not require multiple levels of transmission power for a node (i.e., each node has a fixed transmission range). In this scheme, 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 reduce the number of outgoing packets when the coefficient matrix has full rank of K). We investigate how to choose N_l' and N_u' using simulation in Section VI. This scheme is referred to as *redundancy adaptation*.

V. ANALYTICAL STUDY

We now analytically study the performance of the various error-recovery schemes in Section III. Our goal is two-fold: (1) analytically compare the efficiency of the multiple schemes; (2) provide guidance on how to choose parameters in network coding.

We present the numerical analysis for different approaches. We assume there is a default single path with H hops. Multi-path forwarding and network coding use the same multi-path 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. 2). 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

$$T = \frac{\sum_{i=1}^H T_i}{R} \quad (1)$$

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.

A. Analysis of Single-path Forwarding

We analyze the default single path from the source to the sink with H hops. Consider an arbitrary packet P , because each hop suffers the same packet loss rate p , the probability that one packet could transfer i hop(s), p_i ($1 \leq i \leq H$), is obtained as

$$p_i = (1 - p)^i \quad (2)$$

So the successful delivery probability R after H -hop transmissions is p_h .

As the single path forwarding, one hop means one transmission. So the traffic on the i th hop for a single packet should be

$$T_i = \begin{cases} 1, & i = 1 \\ p_{i-1}, & 2 \leq i \leq H \end{cases} \quad (3)$$

Using these R and T_i , we obtain the normalized energy consumption from (1).

B. Analysis of End-to-end FEC

We consider an arbitrary generation of K packets with S packets redundancy. This means one generation is encoded into $K + S$ packets. Let R' and T' denote the successful delivery probability and the average number of transmissions for any packet out of these $K + S$ encoded packets. From the analysis of single-path forwarding, we directly obtain

$$R' = (1 - p)^H \quad (4)$$

$$T' = 1 + \sum_{i=2}^H (1 - p)^{i-1} \quad (5)$$

At the sink, we assume any K packets from this generation could recover the original packets. So the final successful delivery ratio for this generation is

$$R = 1 - \sum_{i=0}^{K-1} \binom{K+S}{i} R'^i (1 - R')^{K+S-i} \quad (6)$$

Then the normalized energy consumption is

$$T = \frac{(K+S)T'}{R} \quad (7)$$

C. Analysis of Hop-by-hop FEC

The difference with end-to-end FEC is that all relays decode first when possible, then encode this generation again to keep the redundancy. We still encode each generation into $K + S$ packets. It is similar with single-path forwarding if we treat the generation as one packet. So the generation loss rate p' for one hop is

$$p' = 1 - \sum_{i=0}^{K-1} \binom{K+S}{i} p^i (1 - p)^{K+S-i} \quad (8)$$

and the number of the i -th hop transmission is

$$T_i = \begin{cases} K + S, & i = 1 \\ (K + S)(1 - p')^{i-1}, & 2 \leq i \leq H \end{cases} \quad (9)$$

D. Analysis of Multi-path 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 , $n = 0, \dots, N_i$. Assume that packet losses are independent. Then

$$\alpha_i = \begin{cases} 1 - p & i = 1 \\ \sum_{n=0}^{N_{i-1}} \alpha_{i-1,n} (1 - p^n), & 2 \leq i \leq H \end{cases} \quad (10)$$

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

$$\alpha_{i,n} = \binom{N_i}{n} \alpha_i^n (1 - \alpha_i)^{N_i - n}, n = 0, \dots, N_i \quad (11)$$

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

$$T_i = \begin{cases} 1, & i = 1 \\ \alpha_{i-1} N_{i-1}, & 2 \leq i \leq H \end{cases} \quad (12)$$

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

E. 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 [5]. 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 $0 \leq k < K$) or at least k packets (when $k = K$) from all nodes in the previous relay set, $1 \leq i \leq H$. Since the sink is in the H -th relay set and the generation is arbitrary, we have $R = \beta_{H,K}$.

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

$$\beta_{1,k} = \begin{cases} \binom{K'}{k} (1 - p)^k p^{K' - k}, & 0 \leq k < K \\ 1 - \sum_{j=0}^{K-1} \beta_{1,j} & k = K \end{cases} \quad (13)$$

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

For $i \geq 1$, $0 \leq k < K$, 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, $1 \leq i \leq H$, $1 \leq j \leq N_{i-1}$, $0 \leq k < K$. Since each relay transmits no more than K packets, we have

$$\gamma_{i,j,k} = \sum_{n=k}^K \beta_{i-1,k} \binom{n}{k} (1 - p)^k p^{n-k} \quad (14)$$

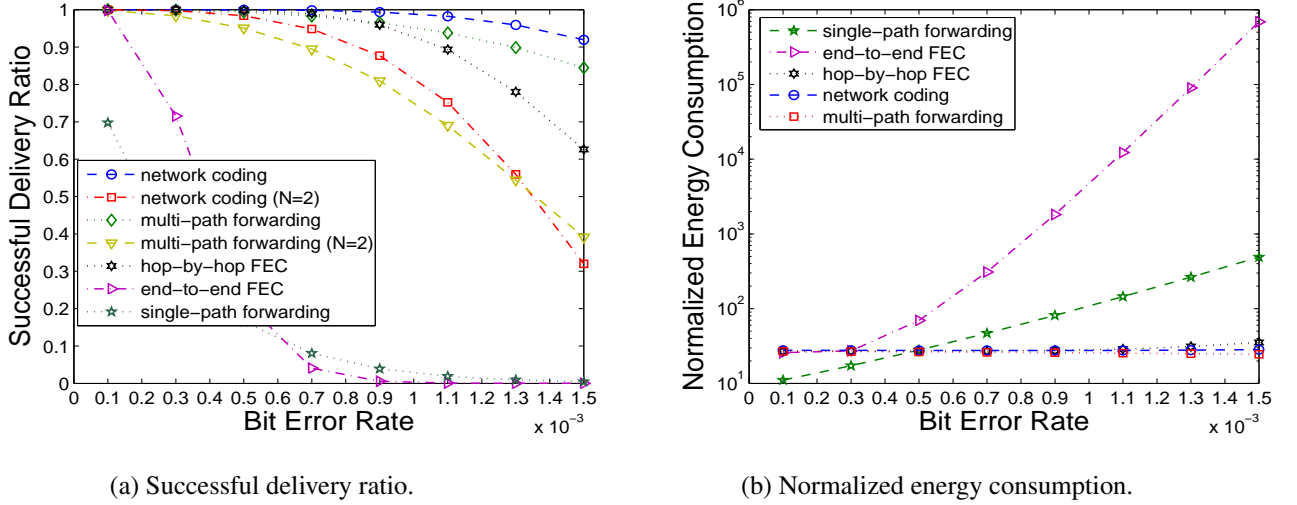


Fig. 3. Numerical results, $H = 9$, $N = 3$ unless specified.

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 $\sum_{j=1}^{N_i} k_j = k$, $k_j = 0, \dots, k$. That is,

$$\beta_{i+1,k} = \sum_{k_j=0,\dots,k \text{ s.t. } \sum_{j=1}^{N_i} k_j = k} \prod_{j=1}^{N_i} \gamma_{i+1,j,k_j} \quad (15)$$

For a small generation size K , the above quantity is easy to compute. We use small K (e.g., $K = 3$) since our study [7] indicates that it is sufficient to achieve good performance using small K (also confirmed by simulation in the settings of Section VI).

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

$$\beta_{i+1,K} = 1 - \sum_{k=0}^{K-1} \beta_{i+1,k} \quad (16)$$

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

$$T_i = \begin{cases} K'/K, & i = 1 \\ \frac{N_{i-1}}{K} \sum_{k=0}^K k \beta_{i-1,k}, & 2 \leq i \leq H \end{cases} \quad (17)$$

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

F. Numerical Results

We next compare the multiple 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., $N_i = N, i = 1, \dots, H$. 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. 3 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. This implies that a node should have 3 downstream neighbors for efficient error recovery (under our assumptions, each node has N downstream neighbors).

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, 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.

VI. 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 $1 \text{ km} \times 1 \text{ km} \times 1 \text{ km}$. 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) [4]. 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} [5]. Therefore, each packet is 53 bytes (including 3-byte encoding vector) under network coding. 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

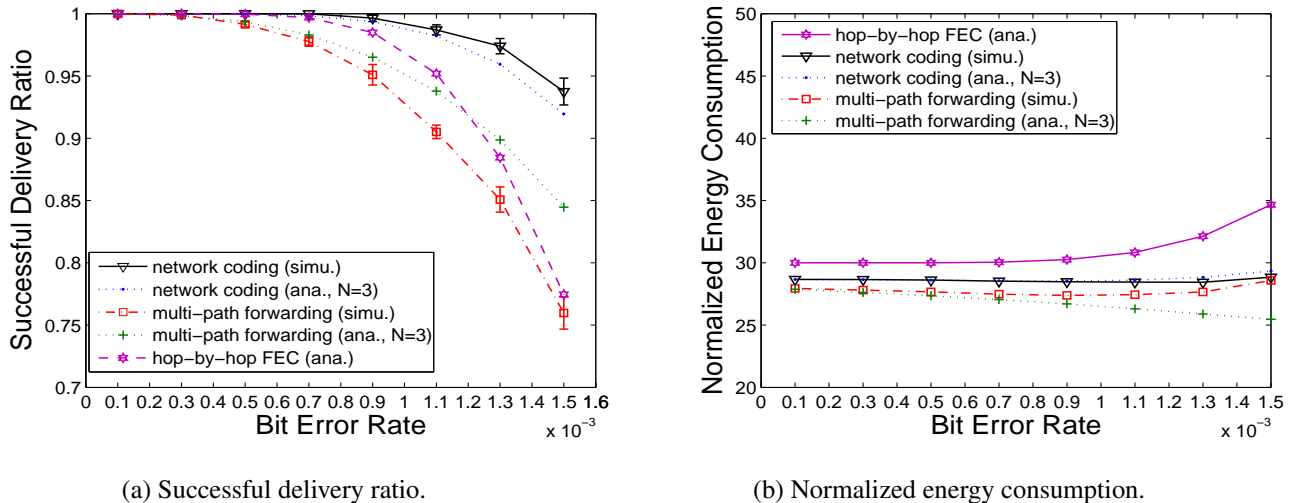


Fig. 4. Simulation results under grid random deployment.

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.

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 multi-path forwarding in the following.

A. Performance under Grid Random Deployment

In grid random deployment, the target area is divided into 125 grids, each of 20 m × 20 m × 20 m. Each grid contains 2 nodes, randomly distributed in the grid. Based on the analytical results in Section V, we set the transmission power and pipe radius of a node to cover 3 to 4 downstream neighbors. This is achieved when each node uses a transmission range of 300 m and a pipe radius of 150 m.

Figures 4 (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 higher than those from the simulation. This is might be because we assume a node can hear from all nodes from its previous relay set in the analysis and provides a overestimate of the successful delivery ratio. We observe that network coding provides a significantly better error recovery than multipath forwarding for high bit error rate. 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

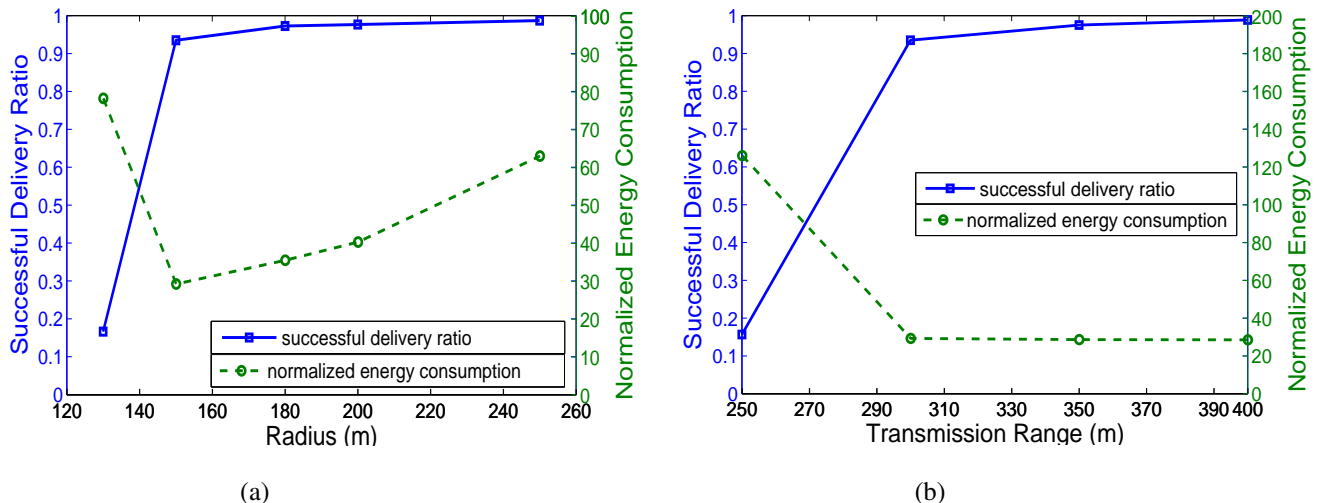


Fig. 5. Successful delivery ratio and normalized energy consumption under grid random deployment: (a) Transmission range is 300 m, (b) Pipe radius is 150 m.

packets in multipath forwarding).

For the sake of comparison, we also plot the analytical result under hop-by-hop FEC in Fig. 4. 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 block 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 5(a) and (b) respectively, where the bit error rate is 1.5×10^{-3} . In both cases, we observe that a good balance between successful delivery ratio and normalized 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).

In our approach, we allow the source to do coding first to avoid the first hop loss. Fig 6 shows the successful delivery ratio when we add different amount of redundancy into source. If we do not add any redundancy, it means the source directly send out original packets. we find the successful delivery ratio is very low because of the loss in the first hop from the source. When we add redundancy into the source, the successful delivery ratio increases significantly. This indicates the importance of the first hop redundancy to avoid the first hop loss. However, too much redundancy is not necessary because it will bring more energy consumption (not plotted).

In practice, the generation size is an important issue because it decides the overhead of an encoded packet (coding

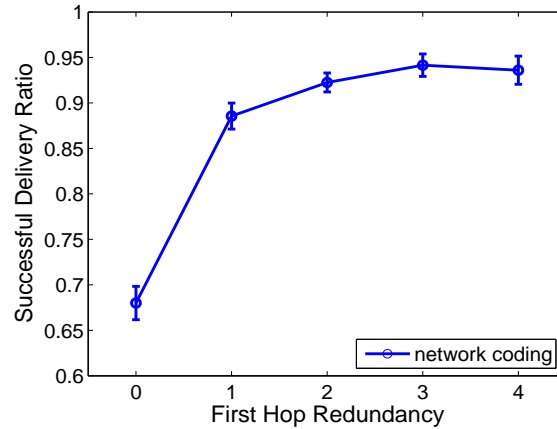


Fig. 6. Successful delivery ratio under different first hop redundancy.

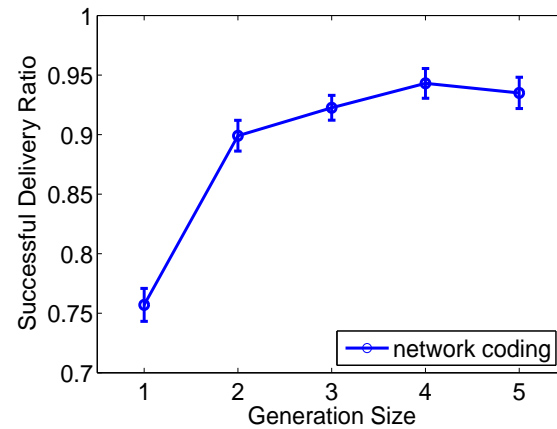


Fig. 7. Successful delivery ratio under different generation size.

vector). In Fig 7, we examined the impact of generation size, if generation size is 1, it is the same as multi-path forwarding, otherwise, we observed the benefit of network coding along with the increased successful delivery ratio. However, too large generation size even reduces the successful delivery ratio under high bit error rate, because it becomes difficult to receive enough packets for the same generation.

B. 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 (The transmission range of the nodes varies from 100 to 400

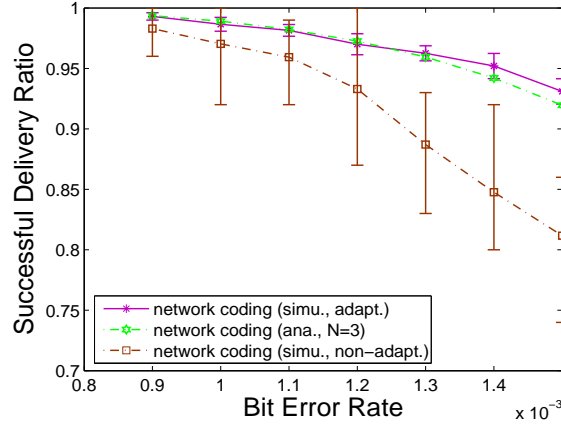


Fig. 8. Transmission-range adaption in uniform random deployment.

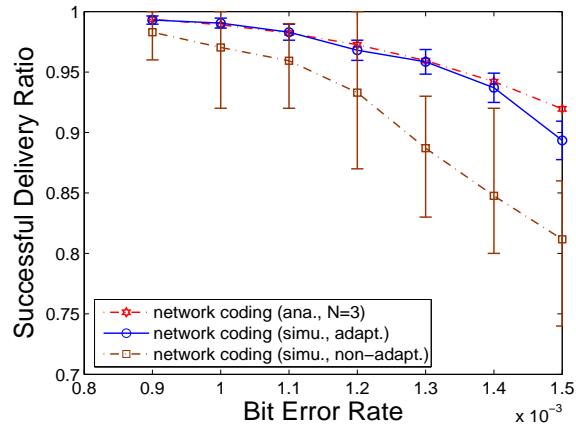


Fig. 9. Redundancy adaption in uniform random deployment.

m). Fig. 8 plots the successful delivery ratio under network coding. The confidence intervals are from 20 simulation runs. 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 also plot the successful delivery ratio when all nodes use a transmission range of 300 m, which is significantly lower than that under transmission-range adaptation. Furthermore, the normalized energy consumption with transmission-range adaptation is lower than that when all nodes use the same transmission range (not plotted).

We next present the results when all nodes use the same transmission range of 300 m and adjusts the amount of redundancy according to the number of its downstream neighbors. In Fig. 9, a node adds one more outgoing packet when it has less than 3 downstream neighbors and remove 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.

VII. CONCLUSION 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 our 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 most efficient among the multiple schemes. Finally, we evaluated the performance of our scheme using simulation. Our simulation results confirmed the analytical study that our scheme is efficient in both error recovery and energy consumption.

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

REFERENCES

- [1] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for efficient communication in underwater acoustic sensor networks," *ACM SIGBED Review*, vol. 1, July 2004.
- [2] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking," in *Proceedings of the IEEE Wireless Communications and Networking Conference, Las Vegas, Nevada, USA*.
- [3] J. H. Cui, J. Kong, M. Gerla, and S. Zhou, "Challenges: Building scalable mobile underwater wireless sensor networks for aquatic applications," in *IEEE Network, Special Issue on Wireless Sensor Networking*, June 2006.
- [4] P. Xie, J. H. Cui, and L. Lao, "VBF: Vector-based forwarding protocol for underwater sensor networks," in *Proceedings of IFIP Networking'06, Coimbra, Portugal*, May 2006.
- [5] T. Ho, R. Koetter, M. Medard, D. R. Karger, and M. Effros, "The benefits of coding over routing in a randomized setting," in *International Symposium on Information Theory (ISIT)*, 2003.
- [6] W. K. Seah and H. Tan, "Multipath virtual sink architecture for underwater sensor networks," in *Proceedings of the MTS/IEEE OCEANS2006 Asia Pacific Conference*, May 2006.
- [7] Z. Guo, P. Xie, J.-H. Cui, and B. Wang, "On applying network coding to underwater sensor networks," in *Proceedings of ACM WUWNet'06, Los angeles, CA*, September 2006.
- [8] C. Fragouli, J.-Y. L. Boudec, and J. Widmer, "Network coding: An instant primer," *ACM SIGCOMM Computer Communication Review*, January 2006.
- [9] V. Chandrasekhar, W. K. Seah, Y. S. Choo, and H. V. Ee, "Localization in underwater sensor networks - survey and challenges," in *Proceedings of ACM WUWNet'06, Los angeles, CA*.
- [10] J. Wills, W. Ye, and J. Heidemann, "Low-power acoustic modem for dense underwater sensor networks," in *Proceedings of ACM WUWNet'06, Los angeles, CA*, September 2006.