A Study on Network Coding in Underwater Networks

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***Abstract*—In this paper, the performance of network coding in underwater acoustic networks is evaluated. The objective of this study is to determine the suitability of using network coding for error recovery in the high error rate underwater acoustic channel; and if so, what parameter settings should be used for a given network so that it can achieve the desired performance. Our study of network coding is conducted independently of Medium Access Control (MAC) and routing protocols. Thus, the results and findings can be applied and used to understand underwater network coding's behavior in a more generic network scenario.**

I. Introduction

In contrast to terrestrial wireless networks that usually rely on radio waves for communication, underwater networks mainly rely on acoustic waves, which results in unique properties such as slow propagation speed, and low bit rate. In addition, the channel's variability and the presence of high ambient noise often lead to high bit error rate.

Traditionally, ARQ (Automatic Repeat Request) and FEC (Forward Error Correction) techniques have been used to tackle channel errors [1]. In ARQ-based schemes, a sender retransmits a packet if it receives some feedback from either the next-hop or the destination node that the packet has been lost, or if it experiences a timeout. In the underwater acoustic channel, an ARQ-based scheme may induce long waiting time before a lost packet can be retransmitted, thus exacerbating the long delays already caused by the slow propagation speed. On the other hand, FEC-based schemes add extra redundancy to the packet before transmission. With strict bandwidth and energy constraints, as well as a highly dynamic channel, the right amount of redundancy may be difficult to determine.

In recent years, network coding has become a very active area of research [2]–[7]. With network coding, an intermediate node may combine packets that it has previously received; this leads to higher robustness against packet losses, since the destination node would still be able to extract the original packets when it receives a sufficient number of packets that satisfy certain properties. It has been shown to be a promising technique that could potentially help networks achieve lower packet delays, as well as high packet delivery ratio (PDR) and energy efficiency [4]–[6].

Currently, the existing works in the area of underwater network coding are still limited since the idea itself was just recently proposed in 2000 for wired networks [8]. In the following, we summarize some of these works. In [4], [5], Lucani *et al.* study the performance of network coding against different routing schemes (e.g., routing using end-to-end acknowledgment, routing using windowing, routing using link-by-link acknowledgment, etc.) in a concatenated unicast underwater acoustic network. According to their results, network coding with implicit acknowledgment outperforms all other routings in terms of both delay and energy efficiency. The authors also propose in [5], a network coding based lower bound for transmission power for concatenated unicast underwater acoustic networks.

In [6], Guo *et al.* attempt to exploit network coding for efficient error recovery for underwater sensor networks. In their study, three different schemes (single-path routing, multipath routing, and network coding coupled with a routing scheme (VBF [9])) are evaluated. Their simulation results show that among the three studied schemes, network coding with source coding performs the best in term of PDR. However, this superior performance is achieved at the cost of higher computations at the node and higher energy usage in the overall packet transmissions. Later in [7], Guo *et al.* extend this work to include the theoretical analysis of the PDR and the energy consumption for both the multipath routing and the network coding.

We devote this paper to the study of network coding's behavior in underwater networks. The key differences of our work from [6] and [7] are that, (i) our study is independent of the type of routing scheme used, and (ii) our study also focuses on identifying the suitable network topology for applying network coding. Therefore, our results can be applied in a more generic way. The remainder of this paper is organized as follows. In the next section, we present the concept of underwater network coding in detail. We then describe in Section III the simulations that we have carried out to compare the performance of network coding with multipath routing, and we present the corresponding results in Section IV. In Section V, we provide a discussion on the guidelines and recommendations when using network coding. Finally, we give our conclusions in Section VI.

II. Underwater Network Coding

In this paper, we have adopted linear network coding [10]. In this type of coding, the encoded packet is a linear combination of the original packets, and all computations (e.g., addition, multiplication) are performed over a finite field $\mathbb{F}_s$. For any given set of original packets, $\mathbf{O} = (O_1, O_2, ...)$, the source node (S) groups packets into generations, where each generation $\mathbf{G}_i = (O_{g(i-1)+1}, ..., O_{ig})$ consists of g packets. For each generation, the source node performs linear encoding over packets belonging to that same generation, so as to obtain

G coded packets, where $G \geq g$. If $G = g$, there is no redundancy added at the source; otherwise, *redundancy* is said to be added at the source with a ratio of $(G-g)/g$. In order to obtain a coded packet X, the source node uniformly selects e_j from $\mathbb{F}_s$ to build an encoding vector, $\mathbf{e}$, where $\mathbf{e} = (e_1, ..., e_g)$. The source node then uses the following equation to obtain X:

$$X = \sum_{j=1}^{g} e_j O_j. \tag{1}$$

The above equation also shows that each encoded packet carries information from multiple original packets. In order to avoid any confusion, we refer to the transmission of a train of coded packets as a "block transmission". Since the encoding vector is selected locally and randomly at the node, the node needs to attach the encoding vector $\mathbf{e}_k$ along with every X_k sent, so as to facilitate the decoding process. In addition, the node also attaches the total number of coded packets (n_{t}) that are being sent for the current block transmission, as well as the transmission order of the packets within the current block.

Upon hearing the first packet in each generation, a relay node stores the packet in its buffer. At the same time, it extracts from the packet the value of n_{t}, as well as the order of this packet within the current block, so as to compute the time at which the current block transmission would end. During this period of time, the node keeps listening for more packets. Every time when an additional packet is received by the node, it checks whether the new packet introduces any additional degree of freedom (DOF)[1]; the packet will be inserted into the node's buffer only if it does, since it provides the node with additional information about the generation. If the node has acquired DOF = g, it performs coding to obtain g coded packets and attempts to broadcast these packets immediately[2]. On the other hand, if DOF $< g$ by the time at which the block transmission ends, the node waits further for a duration of W_{avg}, hoping that there may be other incoming packets from other nodes that can provide additional DOF. Once the duration of W_{avg} is over, the node generates $l = \min(\text{DOF}, g)$ coded packets and then attempts to broadcast these packets. The main objective of allowing the relay node to transmit only $\min(\text{DOF}, g)$ coded packets is to limit the number of transmissions and consequently limit the network's energy consumption.

It is important to mention that the relay node can actually perform encoding directly on the previously coded packets without the need to decode them first. In order to re-encode the l coded packets, $(X_1, ..., X_l)$, the node simply selects l coefficients randomly from $\mathbb{F}_s$ to form its "local encoding vector ($\mathbf{f}$)", where $\mathbf{f} = (f_1, ..., f_l)$. Next, it obtains a new coded packet (X') and a new encoding vector ($\mathbf{e}'$) using (2) and (3), respectively:

$$X' = \sum_{j=1}^{l} f_j X_j, \tag{2}$$

$$\mathbf{e}' = \sum_{j=1}^{l} f_j \mathbf{e}_j. \tag{3}$$

Note that the node only performs network coding on packets that are in the same generation. The vector $\mathbf{e}'$ from (3) is then sent along with the coded packet instead of $\mathbf{f}$ since it provides information about the coefficients of the original packets that are used to form X'.

If the receiving node is a destination node, it decodes the received packets by solving a system of linear equations of order l (DOF = l), in order to obtain the g original packets.

$$X_k = \sum_{j=1}^{g} \mathbf{e}_k O_j \quad \forall\, 1 \leq k \leq l \ , \tag{4}$$

where $\mathbf{e}_k$ is the encoding vector of encoded packet k (i.e., X_k). Note that (4) is mathematically solvable only if $l = g$.

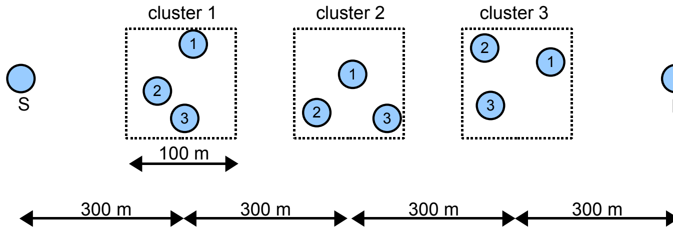


Fig. 1. An example of a cluster string topology with $H = 4$ and $n = 3$.

III. Simulation Setup

In our simulations, the network topology used is a 2-D network with the "cluster string topology [11]", as shown in Fig. 1. There is one source node (S) and one sink node (D), while all other nodes are acting as relay nodes. All sensor nodes are static and are equipped with omnidirectional modems which operate at a fixed data rate of 2400 bps. The source and the sink are H hops apart and are connected to each other through the relay nodes. In each hop, h, where $h = 1, 2, ..., H-1$, there is a corresponding "cluster", in which n relay nodes are uniformly distributed. The h^{th} cluster refers to a square area of size 100×100 m^2 with its center located at $(300h, 50)$. Moreover, the cluster's alignment is such that all of its sides are parallel to either the x- or the y-axis. It is assumed that a transmission from any node within a cluster can be heard by all the other nodes located in the same cluster and also the nodes located in the adjacent clusters. The total area of interest has a dimension of $300H \times 100$ m^2. The source node and the sink node are located at $(0, 50)$ and $(300H, 50)$, respectively.

Each link is assumed to have equal probability of packet error (PER) which is denoted as p. Also, the loss on different links is assumed to be independent. In order to be able to study the behavior of network coding independently of the

[1] In this paper, DOF refers to the number of linearly independent packets.

[2] The actual time at which the node broadcasts its coded packets depends on the MAC scheme.

MAC protocol used, we assume that a node is able to receive multiple packets simultaneously and transmit its transmission block at any instance without causing any packet collision. As a result, the loss of packets is solely caused by channel error. We also assume that the speed of sound in underwater is constant at 1500 m/s and the packet length is 2400 bits.

In order to thoroughly understand the behavior of network coding in underwater networks, the effects of the following parameters are studied: level of redundancy added at the source node (r), generation size (g), W_{avg}, PER (p), number of nodes in each cluster (n), and number of hops in the network (H). Since it was shown in [6] that multipath routing performs much better than single-path routing in underwater acoustic channel, we have chosen multipath routing as our benchmarking scheme. The performance metrics that are used to evaluate each scheme are packet delivery ratio (PDR), data rate (R), and energy consumption (E), each of which is defined as follows:

$$\text{PDR}=\frac{\text{No. of generation received at the destination}}{\text{No. of generations sent from the source}}, \quad (5)$$

$$\text{R}=\frac{g}{\text{Average delay per generation}}, \quad (6)$$

$$\text{E}=\frac{\text{Average energy used per generation}}{g}. \quad (7)$$

The PDR and the data rate specify how robust the scheme is to the channel error, and how fast the scheme can relay the data from the source to the sink, respectively. Energy consumption is used to determine the energy efficiency of the scheme. Ideally, we prefer the scheme that can guarantee high PDR and high data rate while able to maintain low energy consumption.

IV. Simulation Results

A. Simulation Results on Network Coding

The objective of this set of simulations is to gain understanding on the impact of each of the network coding parameters: r, g and W_{avg}. In order to do so, we assume that the network of interest is suitable for applying network coding. The issue of how to determine the suitability of a network for implementing network coding will be studied later in Section IV-B. The network parameters used in this study are assumed as follows: $n = 3, H = 4$. Two different PER levels (p = 0.1 and 0.5) will be studied to see if there is any significant difference in network coding's behavior for different error rate channels.

1) Effect of redundancy (r): Fig. 2(a) shows that increasing redundancy can improve PDR significantly when PER is high (comparing the plot of p = 0.1 with the one of p = 0.5, for the same g). Since channel error is the only cause of packet losses here, one might expect that PDR would keep improving until it reaches PDR = 1 if redundancy continues to increase indefinitely. However, Fig. 2(a) illustrates that PDR can only be improved up to a certain level[3], which could be less than 1. As mentioned in Section II, the "redundancy" refers to the extra packets that are added at the source node. Note that these extra packets do not introduce any new DOF to the generation. When the number of packets sent is already high enough to overcome those packet losses that occurred in the first-hop transmission (the transmission from the source node to the nodes in the first cluster), unnecessarily increasing r will only result in energy wastage without any significant improvement on either PDR or data rate, as shown in Fig. 2.

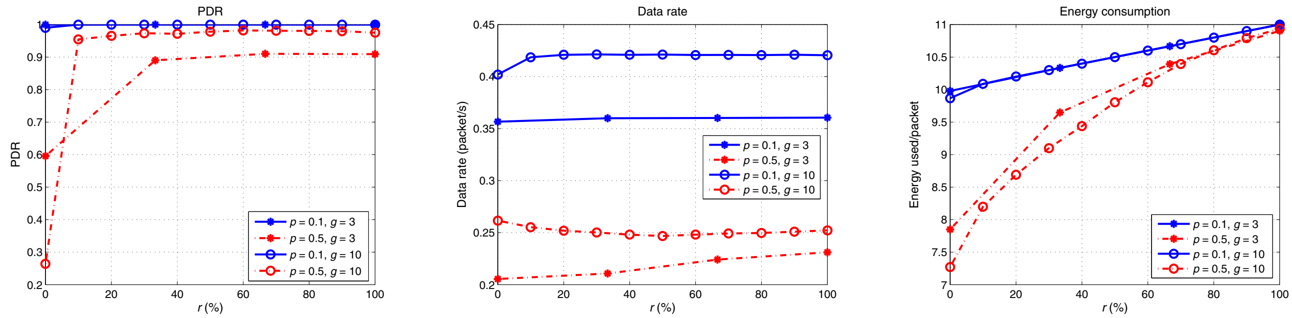
[3]The exact value depends on multiple factors such as network topology, PER, and other network coding parameters.

Since increasing r results in higher PDR but also higher energy consumption (see Fig. 2(c)), determining the right r, so as to achieve a good balance between the gain in PDR and the extra energy spent, is very important. Fig. 2(a) shows that for both generation sizes (e.g., g = 3 and 10), r = 1 packet is good enough to overcome the packet losses in the first-hop transmissions (in the plots, r = 1 packet corresponds to r = 33% and 10% when g = 3 and 10, respectively). As such, we will set r = 1 packet for the rest of the study.

2) Effect of generation size (g): It is shown in Fig. 3(a) that when PER is small, varying the generation size does not affect the PDR. This is because, when PER is small, the number of packet losses are also small. With small number of packet losses, network coding shows that it is capable of recovering all these losses regardless of the generation size, as can be noticed that PDR is always equal to 1. However, when PER is high, a larger generation size results in significant improvement in PDR. This is because a larger generation size tends to increase the number of extra packets (in excess of the generation size) at each hop, which we will elaborate in the following. Let us look at a comparison of what happens in the first-hop transmission for the case where g = 3 and 10. When r = 1, p = 0.5 and g = 3, the source node transmits 4 packets to the n nodes (where n = 3) in the next cluster. On the average, each node receives 2 packets successfully, resulting in a total of 6 packets waiting to be transmitted to the second cluster. Thus, there is a total of 3 extra packets above the generation size that are provided by transmissions from the first cluster. Using a similar computation for the case of r = 1, p = 0.5 and g = 10, we see that there is a total of 16.5 packets on average to be transmitted to the second cluster, of which 6.5 packets serve as extra packets.

In Fig. 3(b) and Fig. 3(c), the data rate and the energy efficiency improve with increasing generation size. However, it is important to note that setting the generation size to a very large value (e.g., 100) may not justify the performance gain due to the resulting higher complexity for encoding and decoding. In practice, the generation size should be set as large as possible subject to the hardware's constraints (e.g., computational resources, buffer space availability).

3) Effect of W_{avg}: In Fig. 4, when PER is small, it can be seen that PDR, data rate and energy consumption are unaffected by the change in W_{avg}. However, significant changes can be observed when the PER is high. As mentioned in Section II that W_{avg} is the duration that the node waits further, for acquiring additional packets, after realizing that it only receives part of the generation. When PER is small, the packets are rarely lost during transmission. Thus, the node usually



(a) (b) (c)

Fig. 2. Effect of redundancy (r).

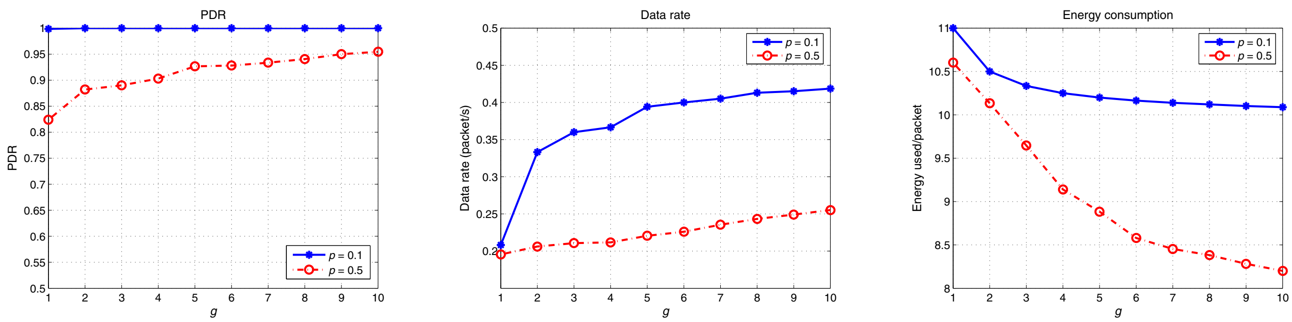


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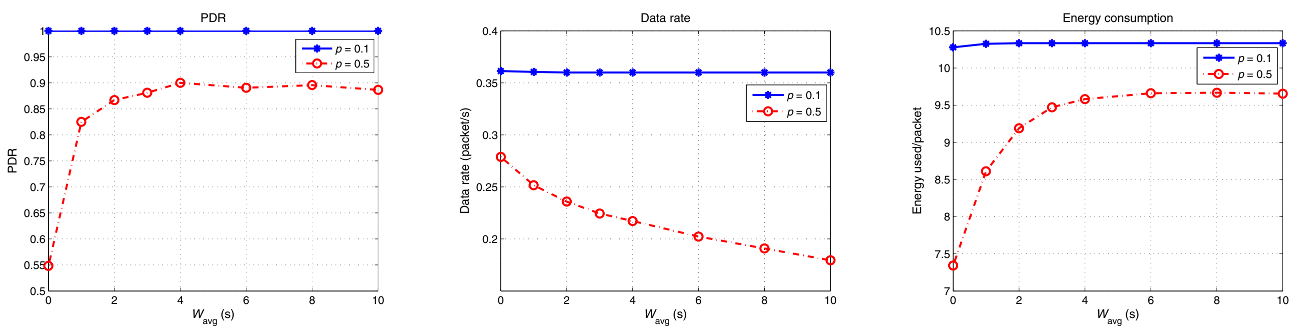
Fig. 3. Effect of generation size (g).



(a) (b) (c)

Fig. 4. Effect of W_{avg}.

receives the whole generation successfully and never needs to deal with the parameter W_{avg}. Even in the case that the node does not receive the whole generation, it is highly likely that the neighboring nodes will provide additional packets shortly after the node has triggered the waiting time W_{avg}. For these reasons, the performance of network coding appears to be independent of W_{avg} when PER is small.

For higher PER, Fig. 4(a) shows that PDR increases with increasing W_{avg}. This trend continues from $W_{\text{avg}} = 0$ until it reaches its saturation point (the point at which $W_{\text{avg}} = 4$ s in the figure). Also, it is observed that network coding performs poorly when $W_{\text{avg}} = 0$. By setting $W_{\text{avg}} = 0$, the network can never utilize the advantage of network coding since the relay nodes will not wait for the additional packets provided by their neighboring nodes, which could have potentially provided extra DOFs. Hence, setting $W_{\text{avg}} = 0$ must be avoided since it can seriously harm the network's overall performance, especially when operating in high PER.

In Fig. 4(b) and 4(c), it is observed that for high PER, increasing W_{avg} results in better PDR but lower energy efficiency and data rate. This suggests that W_{avg} should be set as small as possible subjected to the network's PDR requirement.

B. Performance Comparison between Network Coding and Multipath Routing

In the following, we compare the performance of network coding (NC) with that of multipath routing (MR), based on the same network topology. Particularly, we are interested in finding out if network coding can be generally applied in any network to offer superior performance over multipath routing, or it only performs well in certain network topologies. If the latter is the case, the findings in this study will provide us the guidelines on how to identify such networks. Unless otherwise specified, the parameters in network coding are set as follows: $r = 1$, $g = 3$ and $W_{\text{avg}} = 5$ s. For multipath routing, we also add a redundant packet (at the source node only) for every data packet sent.

1) Effect of PER: As shown in Fig. 5, network coding performs better than multipath routing when PER ≤ 0.55 (this value can vary depending on the parameter settings in network coding). Within this range of PER, network coding offers higher PDR, higher data rate, as well as better energy efficiency than multipath routing. However, when PER > 0.55, the PDR of network coding drops rapidly as the PER increases, and becomes lower than that of multipath routing. This indicates that network coding, under the current parameter settings, can no longer cope with the high number of packet losses that are caused by high PER. As mentioned earlier, in network coding, the destination node requires the reception of g encoded packets to be able to decode the generation. In very high PER, it is highly likely that the sink node receives less than g packets such that the generation cannot be decoded. This results in a sharp drop in PDR, as can be seen in Fig. 5(a).

It is important to note that, although Fig. 5 shows the impact of PER variation over a very large range (from p = 0.1 to 0.8), we are more interested in the range of p = 0.1 to 0.5 since this is typically the range encountered in the real scenario[4]. Within such range, network coding with our current settings can ensure its superior performance over multipath routing.

2) Effect of number of nodes within the cluster (n): In Fig. 6(a), the PDR of both network coding and multipath routing increase with increasing n. This is quite intuitive since higher n results in higher number of paths from the source node to the sink node. The higher number of paths lead to higher number of transmissions, and also higher number of extra packets that can be used to recover the lost packets.

It is also observed that both network coding and multipath routing perform poorly in a single-path network (where $n = 1$), especially in high PER. This is because there is no error recovery mechanism available in such a network, since there is no way that the node can possibly find additional packets to replace the lost ones. This implies that a network with multiple paths between the source and destination nodes is a core requirement in both network coding and multipath routing to recover lost packets. Also, we notice that network coding has lower PDR than multipath routing in a single-path network. Again, recall the requirement in network coding that the destination node requires the reception of g packets to be able to decode the generation; when there is only a single path, the sink node frequently fails to receive g packets, leading to a low PDR as shown in Fig. 6(a). From these observations, it is important to keep in mind that, (i) single-path routing without any coupling with additional error recovery scheme (e.g., ARQ, FEC, etc.) should not be implemented in a high error rate channel, and (ii) network coding should be avoided in single-path routing.

As n increases, both network coding and multipath routing can utilize the extra packets provided by multipath transmissions, yielding better PDR. Although both schemes perform much better when n increases from 1 to 2, multipath routing continues to have better PDR (look at the plots of both schemes when p = 0.5). Network coding shows superior PDR over multipath routing only when $n \geq 3$. This suggests that the network must provide enough multiple paths in order to fully utilize the benefits of network coding.

We now use Fig. 6(a) and Fig. 6(c) to highlight the benefits of performing network coding. With the same network topology used and comparable energy consumption, network coding offers better error recovery when the network has sufficient multiple paths, as can be seen from the higher PDR. By performing encoding on packets before transmission, the information of the generation carried in any two encoded packets sent from different relay nodes will hardly be the same (assuming a large field size is used during the encoding process). Because of this, every encoded packet received is very likely to introduce a new DOF (only when the node has not yet received g DOFs). Unlike network coding, a relay node in multipath routing only stores and forwards packets without encoding. As a result, any two packets transmitted from different relay nodes have a much higher chance of carrying the same information of the generation; when this happens, one of the two packets will be discarded if both are received.

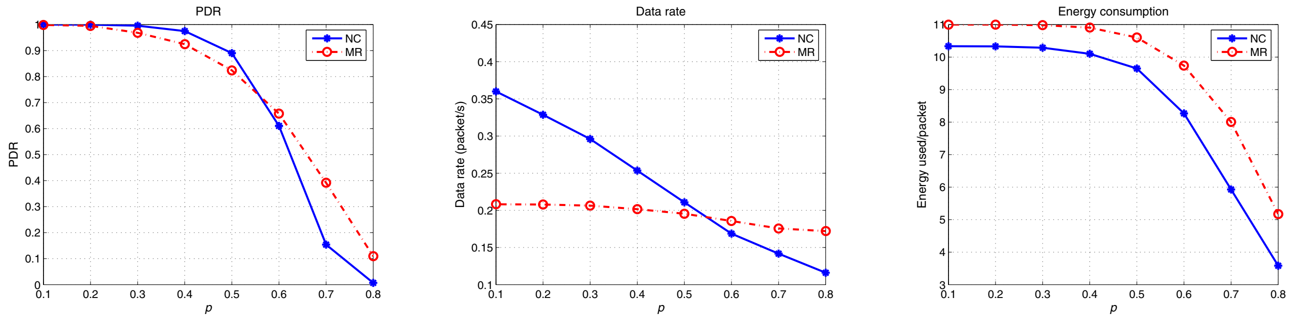
3) Effect of number of hops in the network (H): Besides ensuring that n is large enough to provide multiple paths in the network, Fig. 7(a) shows that H must be greater than 3 so that network coding can outperform multipath routing, when the PER is high. Unlike multipath routing whereby the PDR is unaffected by varying H, the PDR of network coding gradually improves as H increases, until it reaches the saturation point. The poor performance of network coding when $H < 3$ is again caused by the need for g packets to be received at the destination node in order to decode the generation.

Fig. 7(b) and Fig. 7(c) illustrate that for different network sizes (higher H means larger coverage area), network coding always shows either comparable or superior data rate and energy efficiency, as compared to multipath routing.

V. Discussions

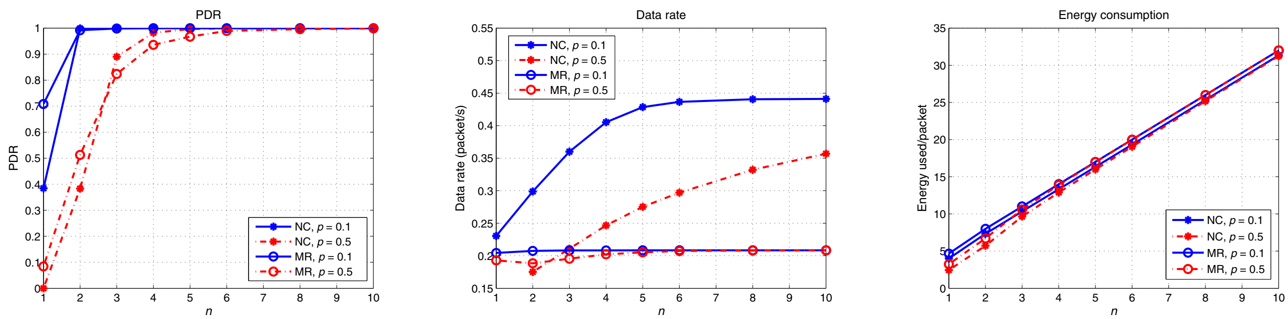
In this section, we provide some guidelines and recommendations that can be helpful when one is considering whether network coding should be applied in a network of interest.

[4]The bit error rate (BER) in underwater acoustic channel usually ranges from 10^{-5} to 10^{-3} [12], which is equivalent to a PER approximately between 0.2 and 0.9 when the packet length is 2400-bit long. However, when BER is high, the packet length can be shortened so that the PER is limited to 0.5.



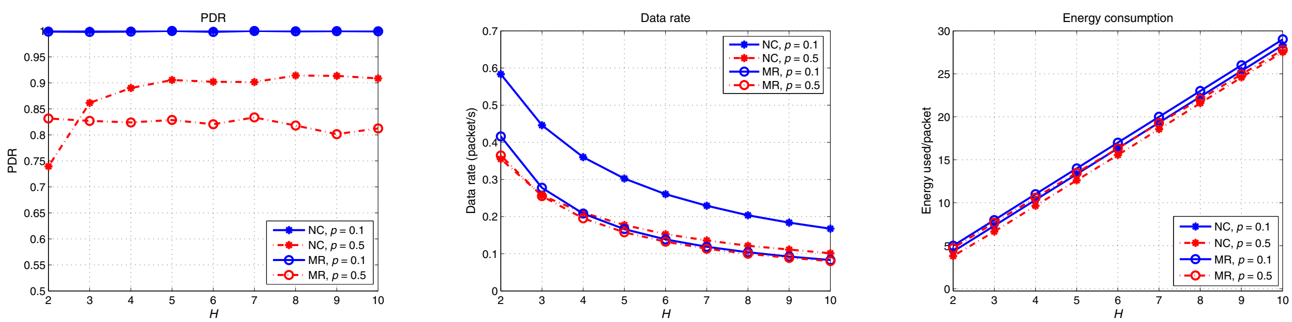
(a) (b) (c)

Fig. 5. Effect of PER.



(a) (b) (c)

Fig. 6. Effect of number of nodes within the cluster (n).



(a) (b) (c)

Fig. 7. Effect of number of hops (H).

A. Determining the Suitability of Network for Applying Network Coding

As shown in Section IV, not every network benefits from applying network coding. Thus, identifying the suitability of the network for applying network coding is absolutely necessary. This is because, when applying network coding, the original intention is to trade higher computational complexity with the gain in network performance. For networks that could hardly fulfill the requirement of receiving g packets at the destination node, poor performance is usually expected and, hence, network coding would have been carried out in vain. In the following, we provide a useful guideline on how to identify this type of network.

Although there are a total of H hops in the network, it is sufficient to focus only on the last-hop transmission[5], since we can assume the best-case analysis. In such analysis, we assume that each of the n nodes in the $(H-1)^{\text{th}}$-cluster has g (the maximum number of encoded packets allowed to be transmitted from each node) encoded packets to be transmitted to the destination node. If the network cannot provide a good probability of receiving a generation successfully at the destination node even when the best case is assumed, we should never apply network coding in such a network. We use (8) to determine the probability $P_{\text{suc,D}}$ that the destination

[5]The transmission from the n relay nodes in the $(H-1)^{\text{th}}$-cluster to the destination node.

node could successfully receive a generation, as follows:

$$P_{\text{suc,D}} = \sum_{m \geq g} \binom{gn}{m} p^{gn-m}(1-p)^m. \tag{8}$$

If $P_{\text{suc,D}}$ for a given network is too small and does not meet the network's PDR requirement, network coding's benefits cannot be realized. In such a network, multipath routing will be more suitable.

In the case where the network administrator has the flexibility to control the network topology (e.g., though power control or node redeployment, etc.), network reconfiguration can also be considered to make the network more suitable for applying network coding.

B. Parameter Settings in Network Coding

Once it has been identified that network coding should be implemented in the network, the setting of its parameters (e.g., r, g, and W_{avg}) is the next issue to be considered. Among the three performance metrics, achieving high PDR should be considered with the highest priority since high PDR usually results in better data rate and higher energy efficiency. From the study in Section IV, it is found that with the right level of r, the other two parameters g and W_{avg} can then be tuned so that the network achieves the desired data rate and energy efficiency. In the following, we present the guideline for determining the right value of r for a given network.

Since the redundancy packets are only added at the source node, we only need to focus on the first-hop transmissions. With r redundancy packets, the source transmits $r+g$ packets to its neighboring nodes. Similar to [7], the probability that a neighboring node (e.g., Node q, where $1 \leq q \leq n$) receives m packets successfully is P_m, which can be computed using (9). P_m is then used in (10) to determine the probability that the cluster successfully receives the generation, which is denoted by $P_{\text{suc,cluster}}$. Note that we use the notation m_q to differentiate among the number of packets received at different nodes.

$$P_m = \binom{r+g}{m} p^{r+g-m}(1-p)^m, \tag{9}$$

$$P_{\text{suc,cluster}} = \sum_{\text{s.t.} \sum_{q=1}^{n} m_q \geq g} \left(\prod_{q=1}^{n} m_q P_{m_q} \right). \tag{10}$$

In order to provide good PDR, $P_{\text{suc,cluster}}$ must be sufficiently high. Although $P_{\text{suc,cluster}}$ only provides us the probability that the first cluster can successfully receive the generation, it is a good parameter which can be used to represent the PDR of the network. This is because the first hop is also the most vulnerable hop that plays a key role in determining whether the destination node would be able to receive the entire generation eventually. If we can guarantee that the first cluster can successfully receive the entire generation, the transmissions in the subsequent hops usually have high success rate since there are n transmitters in each subsequent cluster as compared to just one source node that is transmitting packets at the first hop.

C. Integrating Network Coding with a MAC Protocol

Since we have not included the effect of MAC in our study, we would like to discuss some of the issues that need to be considered and further investigated so that the benefits of network coding can be fully utilized.

Firstly, determining a suitable W_{avg} can now be quite difficult and more complex. When neglecting the effects of MAC, it is shown in Section IV that W_{avg} does not dramatically affect the PDR as long as $W_{\text{avg}} > 0$, making it quite easy to determine W_{avg}. When the effects of MAC are taken into account, it is possible that W_{avg} may have so much influence on the overall network's performance that it could cause network failure if an inappropriate value were chosen. For example, let us consider when CSMA (Carrier Sense Multiple Access) is used as a MAC protocol. If all the nodes in the same cluster were to use the same W_{avg}, there would be excessive packet collisions; in this case, it is more appropriate to choose a different W_{avg} for each node in the cluster using some random distribution. The constant W_{avg} that we have used in our current study is more suitable for a MAC protocol that can receive multiple packets simultaneously, such as CDMA (Code Division Multiple Access).

Secondly, if the MAC protocol used is contention-based, its backoff algorithm must be carefully designed, and the value of W_{avg} must also be properly chosen according to the backoff algorithm. Specifically, they must collectively ensure that when a node encounters a backoff, there is still a high chance that its transmission block could arrive at the next hop before the latter's W_{avg} expires; otherwise, the transmission block will be useless to the next hop since the latter is allowed to transmit each generation only once. This also implies that g should be kept small, since a large g could result in a longer backoff time, which in turn increases the chance that the next hop may find a transmission block arriving too late.

VI. Conclusion and Future Work

In this paper, we have studied network coding's behavior in order to determine its capability to provide efficient error recovery for underwater acoustic networks. From our simulation results, network coding is a promising technique that can provide high PDR, high data rate, as well as good energy efficiency. However, network coding can provide such benefits only if it is implemented in a network that satisfies a certain set of criteria. These include: (i) there are enough multiple paths from the source node to the destination node, and (ii) the total number of hops between the source node and the destination node is large enough to allow network coding to be fully utilized. In the paper, we have also provided some guidelines and discussions on how to choose the parameter values for network coding.

For future work, we plan to better understand the behavior of network coding using theoretical analysis. The understanding obtained from the analysis will then be used to determine the appropriate parameter settings for network coding. Also, since our study has not yet included the effects of MAC, it is also interesting to investigate further on network coding's behavior when it is integrated with a MAC protocol. This will help us identify which type of MAC is the most suitable for integrating with network coding.

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