Opportunistic XOR Network Coding for Multihop Data Delivery in Underwater Acoustic Networks

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***Abstract*—This paper proposes XOR-BiDO, a data delivery scheme (DDS) suited for multihop underwater acoustic networks characterized by regular bidirectional traffic streams. DDSs for multihop underwater networks usually assume a single-sink configuration, where most of the transmissions flow in a single direction. Throughput performance decreases and fairness suffers when such DDSs are subjected to heavy bidirectional traffic streams due to increase of queueing delays at relay nodes. This paper proposes the integration of an *opportunistic* XOR network coding layer into BiDO, a scheme previously designed for single-sink underwater networks. This coding layer actively and opportunistically mixes data frames whenever a coding opportunity arises. By effectively transmitting more data in fewer transmissions at each relay node, the result is a scheme that (1) maximizes usage of the underwater acoustic channel's scarce bandwidth, (2) provides better fairness for bidirectional traffic and (3) improves energy-efficiency of submerged devices, while retaining the *opportunistic*-routing and network-wide overhearing features of BiDO. Using simulations, we demonstrate the network performance improvement of XOR-BiDO in terms of packet latency, fairness and energy-efficiency for bidirectional network traffic. While maintaining comparable reliability over a 10-hop network, XOR-BiDO achieves a 12% improvement in latency and consumes 24% less energy per delivered packet against BiDO.**

I. INTRODUCTION

Communication between submerged nodes over long distances via multihop transmissions is a key requirement in many emerging underwater applications such as the command and control of underwater autonomous vehicles (UAVs), sensor networks etc.

In our previous work [1], we have proposed the *Opportunistic* ARQ with Bidirectional Overhearing or BiDO, a multihop data delivery scheme (DDS) that leverages on the broadcast property as well as spatial and temporal variance of the underwater acoustic channel to perform *opportunistic-routing*, so as to improve reliability, network throughput and energy efficiency. Under favorable channel conditions, data frames can skip hops, arriving at the sink in fewer hops.

In addition, implicit acknowledgements through the overhearing of downstream data and acknowledgement (ACK) frames help to curb redundancy and purge duplicates. The time diagram for a single source and sink network in Fig. 1 summarizes these features. A time-division multiple access (TDMA) based medium access control (MAC) protocol plays the role in eliminating all packet collisions so as to increase the possibility of overhearing by all nodes in the network.

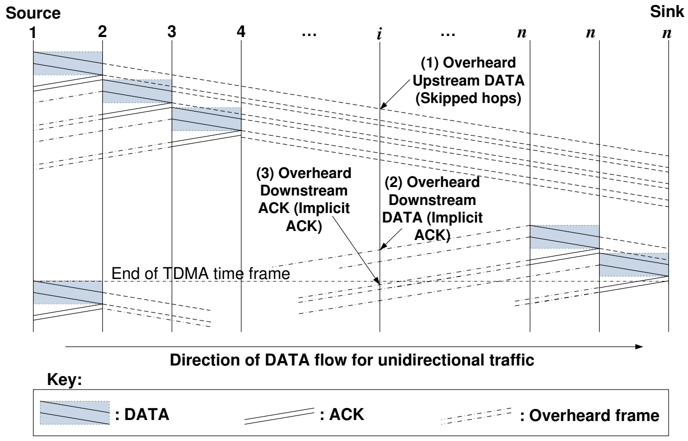

Fig. 1. Time diagram summarizing the features of BiDO proposed in [1] for a single source/sink network. (1): Overheard upstream DATA can skip hops, speeding up delivery. (2) & (3): Overheard downstream DATA & ACK used as implicit acknowledgements to purge duplicates.

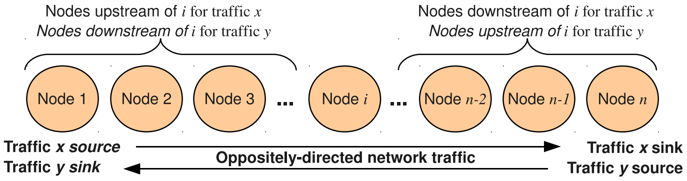

Fig. 2. A simple linearly-arranged underwater network with bidirectional traffic flowing towards opposite ends of the network. Terminology of *upstream* and *downstream* for a particular traffic stream is illustrated.

However, schemes designed for single sink networks do not cope well when subjected to bidirectional traffic. Fig. 2 illustrates a sample network characterized by such bidirectional traffic streams. It is useful to observe the per-packet end-to-end delay of a 10-hop network running on BiDO. Fig. 3 illustrates this, contrasting packet latencies between when the network is subjected to uni and bidirectional traffic.

Intuitively, the bidirectional traffic simulation with more packets flowing both ways results in a busier network, thereby incurring larger packet latencies due to the buildup of queueing delays at the relay nodes. Packets from flow 1 may need to wait for some packets from flow 2 in the first-in-first-out (FIFO) queue to clear before getting transmitted and vice versa. This is due to the sharing of a single queue amongst packets at each relay node, contributing to the erratic packet latencies of both flow 1 & 2.

The erratic packet latencies can also stem from the spatial

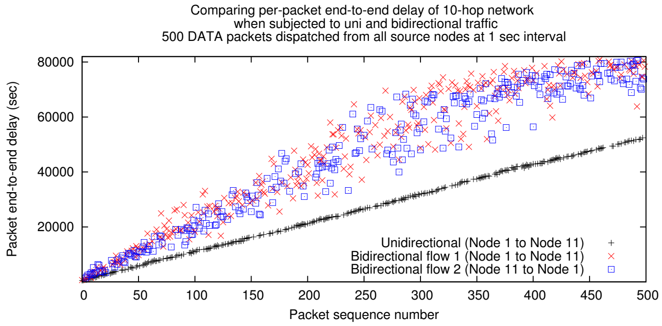

Fig. 3. Per packet end-to-end delay for two simulations of a 10-hop network running on BiDO. The unidirectional simulation has only traffic flowing one way. The bidirectional simulation was subjected to network traffic originating from both Node 1 and Node 11. A higher and erratic packet latency can be observed for the bidirectional simulation.

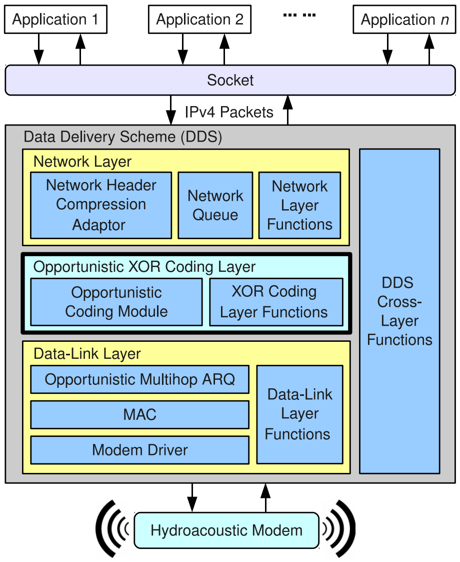

Fig. 4. Network architecture of XOR-BiDO. The new *Opportunistic* XOR Coding Layer is outlined in bold.

and temporal variance of the adverse underwater acoustic channel. In the case of an asymmetric channel, network traffic can flow smoothly in one direction but not the other, leading to a 'pile-up' of packets from the impaired traffic stream at the queues of the relay nodes. This leads to delivery unfairness and erratic packet latencies. For multihop underwater networks with regular bidirectional traffic, network coding could be a solution to the above-mentioned problems.

In recent years, network coding has gained popularity in many applications for its benefits in improving network throughput and energy-efficiency. The novel idea of mixing packets mathematically at relay nodes in multihop networks was first introduced by Ahlswede *et al.* in [2] as a way to attain the maximum possible information flow in a network. In [3], the authors proposed the simple but elegant XOR-coding of two or more packets at the relay nodes in terrestrial multihop networks to reduce total transmissions and increase throughput.

For the underwater acoustic channel characterized by low achievable data rates, long propagation delays and high bit error rates [4], network coding offers significant potential to improving network performance. In [5], Lucani *et al.* suggested several network coding schemes and numerically illustrated their performance gains in underwater networks.

The key contribution of this paper is the seamless integration of the *opportunistic* XOR coding layer with the BiDO DDS from [1]. This additional XOR coding layer in the hybrid scheme is aimed at improving packet latency, fairness and energy efficiency in multihop underwater networks characterized by regular bidirectional traffic. At the same time, the *opportunistic*-routing and network-wide overhearing features of BiDO as illustrated in Fig. 1 are retained.

The rest of this paper is organized as follows: The main features and design specifications of the XOR-BiDO DDS are articulated in Section II. Section III presents the simulation results and analysis. Finally, we provide some concluding remarks and outline directions for future work in Section IV.

II. DESIGN SPECIFICATIONS OF THE XOR-BIDO DATA DELIVERY SCHEME

XOR-BiDO is implemented using a cross-layer network architecture as shown in Fig. 4. The architecture is similar to that in [1], with the addition of the *opportunistic* XOR Coding Layer. The insertion of this coding layer in between the Network and Data-Link Layer (DLL) of the original BiDO network architecture is inspired by the design from [3].

The XOR Coding layer actively searches for coding opportunities from both hop-by-hop and *opportunistically* overheard transmissions. When such an opportunitiy is identified, a relay node effectively increases available bandwidth by transmitting a coded frame crafted from mixing (XOR-ing) two regular DATA frames from opposite traffic streams.

The following details the pertinent components present in this *Opportunistic* XOR Coding Layer:

Opportunistic Coding Module

- *XOR_NW_QUEUE(p)*: Searches the network queue for a *partner frame*[1] q. Returns the partner frame q if such a frame is located in the network queue.
- *swam_left_pool*: Contains DATA frames that were successfully or unsuccessfully (no explicit ACK received) transmitted that are destined to any node to the left (smaller node IP) of the current node. All nodes maintain such a DATA frame pool that has a fixed maximum size. When full, the oldest frame is dropped. A node will

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[1] 'Partner frame' refers to a DATA frame destined for the opposite direction with the frame in question. Only partner frames are coded together in XOR-BiDO.

search for a *key frame*[2] from this pool to decode a coded frame heard from its left (smaller node IP).

- *swam_right_pool*: Identical to *swam_left_pool* except that it stores frames that have 'swam' to the right (larger node IP) of current node. A node will search for a key frame from this pool to decode a coded frame heard from its right (larger node IP). The maintainence of these two data frame pools ensures a high probability of the node being able to decode received coded frames.

XOR Coding Layer Functions

- *XOR_DATA(p,q)*: Encodes two partner frames p & q together, returning the XOR-coded DATA frame.
- *UN_XOR_DATA(x,p)*: Decodes a XOR-coded DATA frame x with a key frame p. If x was a result of xor-coding p and q together previously, this function will return DATA frame q.
- *STORE_PAST_DATA(p)*: Stores a successfully or unsuccessfully transmitted DATA frame into the relevant pools (*swam_left_pool* or *swam_right_pool*).

A. Frame Formats

Fig. 5 shows the three types of frame formats used in the XOR-BiDO DDS.

- Regular DATA frame: This will be transmitted either when there are no coding opportunities available at the moment, or if the payload in question originated from the node itself. Packets originating from the node itself are always sent in the clear to ensure XOR-ed frames are decodable by intended recipients.
- XOR-coded DATA frame: Fields that are required in the decoding process are trasmitted uncoded in the frame header, whereas all other fields are XOR-coded. This frame has a minimal 3 bytes overhead compared to the regular DATA frame. A relatively large payload will almost eliminate the effects of this overhead.
- Network ACK frame: Sent as an explicit acknowledgent for both clear and coded transmissions. Pertinent in the correct functionality of the BiDO portion of the DDS by providing network layer information of the DATA it is acknowledging to all nodes that can overhear the ACK in the network. An overheard downstream ACK can serve as an implicit acknowledgement to curb redundancies.

B. Medium Access

Modifications were made to the medium access rules to cater to the fact that each XOR-coded DATA frame is explicitly addressed to the two immediately adjacent nodes at the same time. The TDMA slot duration in BiDO was designed to be just enough for transmission of a regular DATA frame and receipt of an ACK.

The XOR-BiDO DDS uses XOR-coded frames that requires explicit acknowledgement from both recipients (the immediate adjacent neighbors) of the coded frame, thereby neccessitating the extension of the slot duration to allow for receipt of two ACKs by the sender. The modified timeslot creates allowance for this while maintaining the collision-free nature of the TDMA MAC.

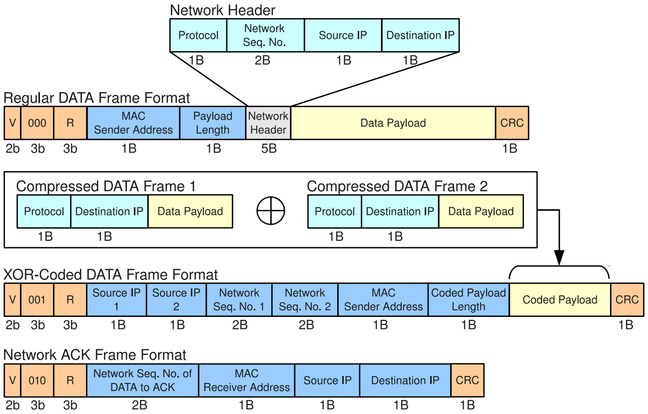

Fig. 5. The three frame formats used in XOR-BiDO. In the event that no coding opportunities are identified by the *Opportunistic* Coding Module or if the payload originated from the node itself, a regular DATA frame will be transmitted. There is a minimal 3-bytes overhead for the coded DATA frame when compared to the regular one.

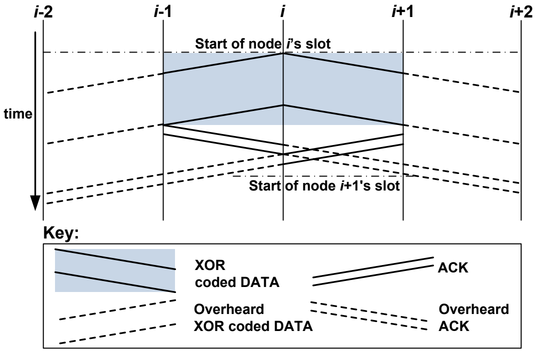

Fig. 6. A close-up of node i's timeslot in XOR-BiDO. Node $i-1$ and $i+1$ will take turns to explicitly transmit an explicit ACK frame to i upon successful receipt of the XOR-coded frame. Allowing node $i-1$ priority in transmitting its acknowledgement first results in a smaller TDMA timeslot that makes better use of the available bandwidth.

With the sequence of nodes' transmission timeslots still ordered in a left-to-right fashion, node i-1 is allowed to first acknowledge a coded frame transmitted by node i, followed by node i+1. This results in a smaller TDMA timeslot (saving of 1 x ACK's transmission delay) to better utilize the available bandwidth.

The following section will explain the salient points of the XOR-BiDO data delivery scheme in detail.

C. XOR-BiDO Protocol Details

XOR-BiDO has so far been described for a linearly-arranged network of that shown in Fig. 2. Nevertheless, the XOR-BiDO DDS can be extended to the general case where each node simultaneously takes on the role of the source, relay and sink at the same time.

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[2] 'Key frame' refers to a regular DATA frame that can be used to decode an XOR-ed DATA frame. A key frame thus 'unlocks' a coded frame.

Pertinent details of algorithms residing in the proposed scheme are described as follows for a sample network (of that shown in Fig. 2):

1) When a regular DATA frame p (p's next hop is $i+1$) at node i is passed downwards to the DLL pending transmission, the *Opportunistic* Coding Module searches the network queue for a coding opportunity. Such an opportunity exists when a partner frame q destined for a sink node in the opposite direction (any of node 1 to $i-1$) is found. A XOR-coded DATA frame $p \oplus q$ will be created and transmitted if such a DATA frame q is found.
2) When a XOR-coded DATA frame $p \oplus q$ from node i is successfully received by both immediate adjacent neighbors, the frame is explicitly and sequentially acknowledged first by node $i-1$ (for DATA frame q), followed by node $i+1$ (for DATA frame p) by transmitting an ACK frame to i, as illustrated in Fig. 6.
3) In the event that p was transmitted successfully (i received explicit ACK from $i+1$) but not q (no ACK heard from $i-1$), transmission of $p \oplus q$ will cease. The *Opportunistic* Coding Module will proceed to search the network queue for a new partner frame that can be coded with q. If such a coding opportunity is non-existent, q will be transmitted as a regular DATA frame, and vice versa.
4) Each individual DATA frame can only be transmitted up to a maximum of T_{max} times at each node, coded or not. A node i thus maintains an individual *transmission_counter* for each of p and q in a coded DATA frame $p \oplus q$. Upon T_{max} transmissions of p in $p \oplus q$, p will be dropped and q XOR-coded with a new partner frame if such a coding opportunity exists. The *transmission_counter* for q is carried over to the new XOR-coded frame.
5) The search for coding opportunities in the network queue will always be done at the very last moment before a node's transmission time slot to maximize the chances of locating a partner frame. This allows the maximum time to receive/overhear partner frames that can be XOR-coded with the next frame in queue. The objective of XOR-BiDO is to transmit coded frames where possible rather than regular ones to maximize throughput.
6) As per BiDO in [1], nodes other than the immediate adjacent neighbors upon opportunistically overhearing a transmission, need not transmit an explicit ACK. It can however decode the overheard coded frame, where the contents can represent a DATA frame that has skipped hops AND/OR implicit ACK.
7) If frame p originates from node i, no coding will be performed on p at i. Coding is only performed by a node on DATA frames it is helping to relay.
8) Most, if not all XOR-coded frames received from a node's left (right), can be decoded by searching for a key frame in the *swam_left_pool* (*swam_right_pool*). Due to the peculiar nature of the underwater acoustic channel, there will instances whereby a node does not possess a key frame to decode a XOR-coded frame. One such scenario occurs when a DATA frame p skip hops, whereby a further node receives p but not the nearer one. The skipped node thus does not possess p as a key frame for any future received coded frames containing p.

III. PERFORMANCE EVALUATION

The proposed XOR-BiDO scheme was implemented and its performance evaluated via simulations on the Qualnet Network Simulator [6]. The performance metrics used for comparison are: (*i*) packet delivery ratio (PDR), (*ii*) average delay (end-to-end) per delivered packet and (*iii*) average network energy consumption per delivered packet. The performance of XOR-BiDO will be compared against BiDO for any network performance improvement.

A. Simulation Parameters

Network topology: The network comprises n nodes arranged uniformly in a linear fashion as illustrated in Fig. 2. The distance between each pair of adjacent nodes is set at 1000 metres. Simulations were performed for different-sized networks, varying from n = 2, 3, ... , 11.

Application: To simulate regular bidirectional traffic, an application is situated at Node 1 and n for all simulations, creating and passing to the network stack 500 packets at 1 second interval. The payloads are sized such that a regular DATA frame will be 1021 bytes and a XOR-coded DATA frame 1024 bytes long at the physical layer.

Channel model: An underwater acoustic channel model based on [4] was used for all acoustic signal transmissions under our simulation model. This was the same model used in simulations for our previous work in [1]. The model accounts for path-loss, ambient noise and propagation delays of the underwater acoustic channel.

Other parameters: The baud-rate of the underwater acoustic modem is set to a nominal value of 10,000 bps.

A simuation is completed when all DATA frames are either delivered to the sink or dropped. The performance metrics plotted in the following section are derived from averaging simulations results (from both applications used to create bidirectional traffic) over 10 trials (with different seed values).

B. Simulation Results & Analysis

Packet Delivery Ratio: The key objective of the simulations is to compare the network performance of XOR-BiDO to BiDO when both schemes are subjected to regular bidirectional traffic. However, it serves us well to first have an overview of the PDR performance of different variants of DDSs running on the same reliability setting. The maximum number of transmissions here refers to the automatic repeat request (ARQ) sub-layer reliability mechanism at each hop, or

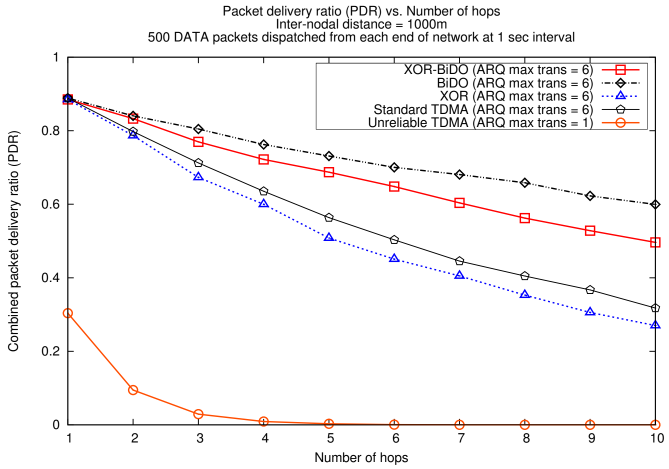

Fig. 7. Simulation results of packet delivery ratio (PDR) plotted against number of hops for different variants of DDSs. Besides XOR-BiDO & BiDO that have been described, three other DDSs' PDR are plotted: (1) XOR DDS contains the XOR-coding functionality but not BiDO, meaning DATA frames have to travel in a strictly hop-by-hop fashion, (2) Standard TDMA contains no XOR-coding or BiDO element, with DATA frames traversing in a strictly hop-by-hop fashion, (3) Unreliable TDMA which operates similarly to Standard TDMA but without any retransmission mechanism.

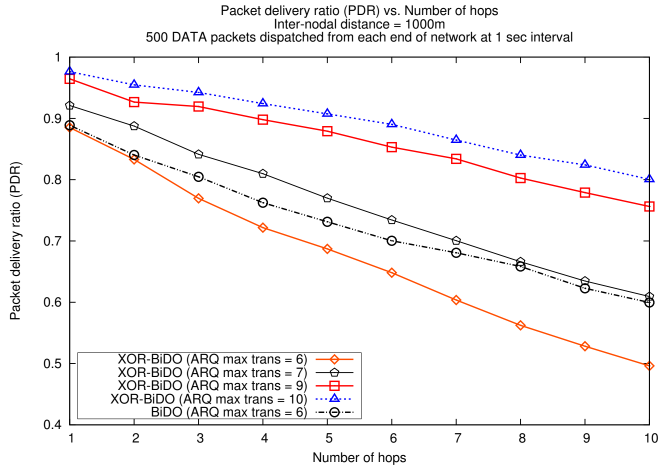

Fig. 8. Simulation results of packet delivery ratio (PDR) plotted against number of hops for XOR-BiDO with varying *ARQ max trans* as compared to the BiDO DDS. At 7 *ARQ max trans* for XOR-BiDO, the PDR performance approximately matches that of BiDO at 6 *ARQ max trans*. XOR-BiDO has a poorer PDR performance as compared to BiDO when using equivalent *ARQ max trans*.

ARQ max trans. It is the maximum number of times a DATA frame can be transmitted at each node before being dropped.

Besides XOR-BiDO and the BiDO DDS that have already been described in detail, three other DDS variants are plotted in Fig. 7: (1) The XOR DDS contains the XOR-coding functionality but without BiDO, meaning DATA frames have to traverse the network in a strictly hop-by-hop fashion. (2) The Standard TDMA DDS is the simplest DDS, requiring DATA frames to traverse in a strictly hop-by-hop fashion with no additional functionality. (3) Finally, the Unreliable TDMA DDS operates identically to the Standard TDMA DDS but without any retransmission mechanism.

The poor PDR performance of the Unreliable TDMA DDS reflects the challenging channel condition of the underwater acoustic medium (30% at 1-hop), and at the same time shows the benefits of having retransmissions at each hop.

We also see that XOR-BiDO and XOR lose out slightly to BiDO and Standard TDMA respectively. The PDR performance degrades with the additional XOR-coding component as compared to its counterpart without coding. This is due to some nodes not being able to decode received XOR-coded DATA frames, thus having to drop them. The reason for this was discussed in Section II-C.

In order to have a fair comparison between XOR-BiDO and BiDO across the other performance metrics, we increase the ARQ's maximum transmissions (*ARQ max trans*) allowed for XOR-BiDO to 7 so as to approximately match the PDR performance with that of BiDO. These results, together with the PDR performance of even higher *ARQ max trans* (9 & 10) are plotted and shown in Fig. 8. It is clear that the PDR performance of XOR-BiDO with 7 *ARQ max trans* almost matches that of BiDO with 6 *ARQ max trans*, and increases as expected with higher *ARQ max trans*.

Packet Latency: We next look at the average end-to-end delay per delivered packet plot in Fig. 9 that corresponds to the PDR plot in Fig. 8. It should be noted that the packet delay in our simulations is calculated at the application layer, thereby taking into account queuing delays at all nodes.

It can be observed that the XOR-BiDO DDS gains significant improvements in packet latency as compared to BiDO. While maintaining comparable PDR performance, the XOR-BiDO DDS achieves a 12% improvement in packet latency over a 10-hop network. Furthermore, looking at both Fig. 8 and 9, we can see that by increasing the *ARQ max trans* to 9, its PDR performance improves by a sizeable amount of 26% against that of BiDO over a 10-hop network, whereas average packet latency of both DDSs becomes comparable.

The simulation results for average packet delay when analyzed together with PDR performance positively shows the advantages of XOR-BiDO over the BiDO DDS when subjected to regular bidirectional traffic. The overhead incurred from having a wider TDMA timeslot and a slightly larger transmission delay due to the bigger frame size of the coded frame is dwarfed by the network performance improvements the XOR-BiDO DDS brings.

XOR-BiDO clearly outperforms BiDO in terms of delay with comparable PDR and vice versa. Depending on the nature of the application, *ARQ max trans* can be tweaked to favor either better performance in PDR, average packet latency, or a balanced improvement in both metrics.

Additionally, it is insightful to study the per received packet end-to-end delay of XOR-BiDO as compared to the BiDO DDS. A plot of individual packet end-to-end delays of one of the traffic streams is shown in Fig. 10. The advantages of the *opportunistic* XOR-coding can be seen from the consistent

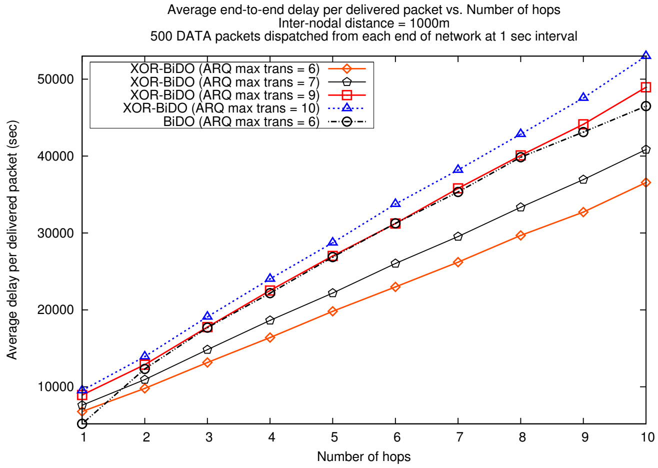

Fig. 9. Simulation results of the average end-to-end delay per delivered packet plotted against number of hops for XOR-BiDO with varying *ARQ max trans* as compared to the BiDO DDS. With a higher *ARQ max trans* of 7, XOR-BiDO outperforms BiDO in terms of average packet latency by 12% while maintaining comparable PDR.

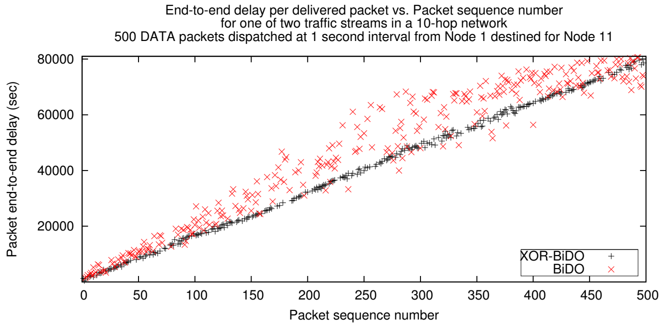

Fig. 10. Per packet end-to-end delay of one of two traffic streams in a 10-hop network running on XOR-BiDO & BiDO. When subjected to bidirectional traffic, the XOR-BiDO DDS results in lower, uniform and predictable packet end-to-end delay, resembling that of a network with only unidirectional traffic.

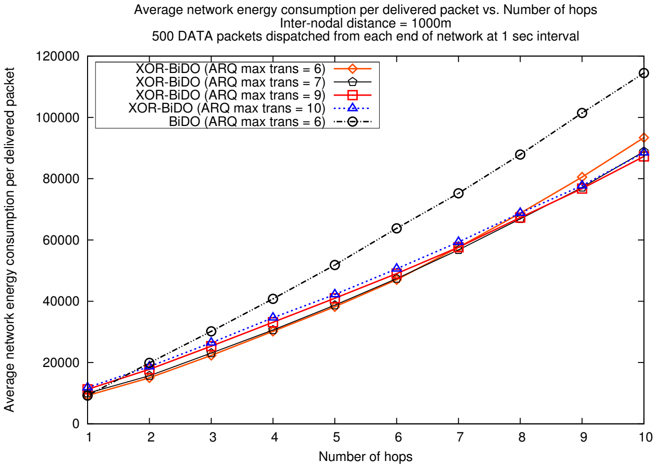

Fig. 11. Simulation results of averaged network energy consumption per delivered packet plotted against the number of hops. Energy-efficiency of XOR-BiDO is consistent despite increasing the *ARQ max trans* up to 10 compared to 6 for BiDO, even outperforming BiDO at *ARQ max trans* of 10.

and predictable behavior of the packet end-to-end delays. This offers delivery fairness for packets from both traffic streams, which is in contrast with the erratic packet delays seen in BiDO.

Energy-Efficiency: A simple energy consumption model was used to investigate the energy-efficiency of XOR-BiDO as compared to the BiDO DDS, whereby the energy cost for transmission is defined as the size of the frame, and that for reception to be half of the former. It is clear that XOR-BiDO outperforms BiDO in terms of energy-efficiency, consuming 24% less energy across the network per delivered packet over a 10-hop network. Energy-efficiency of XOR-BiDO remains pretty consistent despite increasing the *ARQ max trans* from 6 to 10.

IV. CONCLUSION & FUTURE WORK

In this paper, we presented XOR-BiDO, a data delivery scheme suitable for multihop underwater acoustic networks characterized by regular bidirectional traffic. The proposed scheme incorporates *opportunistic* XOR network coding into *Opportunistic* ARQ with Bidirectional Overhearing (BiDO), a data delivery scheme (DDS) previously designed for networks with unidirectional traffic featuring *opportunistic*-routing and network-wide overhearing.

We performed simulation studies to evaluate the performance of XOR-BiDO and showed that it outperforms its counterpart without network coding in terms of reliability, packet latency, delivery fairness and energy-efficiency when subjected to bidirectional traffic.

In the near future, we plan to implement the XOR-BiDO DDS on hydroacoustic modems and evaluate its actual performance in sea trials.

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