Opportunistic ARQ with Bidirectional Overhearing for Reliable Multihop Underwater Networking

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***Abstract*—As reliable data delivery over a long-range single-hop underwater acoustic link is considerably challenging due to severe channel impairments, multihop data transmission schemes over one or more relay nodes have been proposed. In this paper, we propose a data delivery scheme using a fully-*opportunistic* ARQ that employs *bidirectional overhearing*, whereby nodes leverage on the broadcast nature of acoustic channels and their spatial and temporal variance to overhear (*i*) data packets from all upstream (nearer to source) nodes to speed up data delivery and (*ii*) data & acknowledgement packets from all downstream (nearer to sink) nodes as implicit acknowledgements. The cross-layer scheme uses implicit acknowledgements to purge duplicates at both data-link and network layer. We demonstrate using simulations that, when implemented on an Interweaved TDMA MAC scheme, the proposed delivery scheme achieves better reliability, energy-efficiency and latency as compared to non-*opportunistic* or semi-*opportunistic* schemes in multihop underwater acoustic networks with linear topology. Over a 10-hop network, the proposed scheme outperforms its non-*opportunistic* counterpart, delivers 88% more packets, consumes 43% less energy and achieves an 8% improvement in latency (per packet delivered).**

I. INTRODUCTION

Remote sensing applications such as environmental monitoring, disaster prevention, and tactical surveillance are key motivating factors for underwater acoustic networking research [1]. Although the conventional approach of using direct transmission (single-hop) from a source to a sink is simple, it suffers from several disadvantages such as high energy consumption, high bit error rates (BER) and low achievable data rates [2], and is not suitable for tactical surveillance applications. As such, multihop data transmission has become attractive as it can provide higher achievable data rates and lower BER over multiple links of shorter distances [2].

We consider a linear deployment of $n + 1$ nodes, with a single source (node 1) and sink (node n+1), for long-range sensing applications, as illustrated in Figure 1. To achieve reliable end-to-end multihop data delivery, automatic repeat request (ARQ) schemes can be employed to improve the reliability of transmissions at every hop. Lucani *et al.* [3] have shown that hop-by-hop ARQ achieves better performance than its end-to-end counterpart.

However, *strictly* hop-by-hop ARQ schemes do not fully exploit the broadcast property nor consider the spatial/temporal variations of underwater acoustic channels. We explain the resulting inefficiencies by considering a *strictly* hop-by-hop Stop & Wait ARQ scheme over Interweaved TDMA MAC [1], whose timing diagram is given in Figure 2:

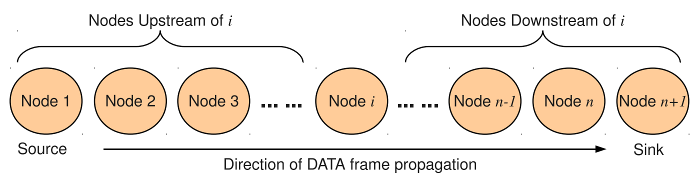

Fig. 1. A n-hop underwater network with linear topology.

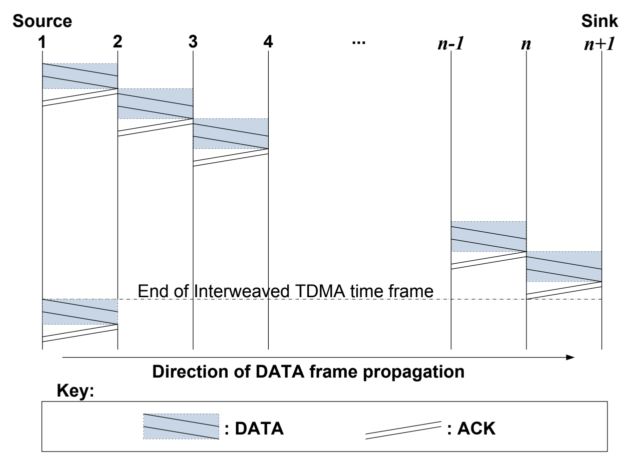

Fig. 2. Timing diagram for *strictly* hop-by-hop Stop & Wait ARQ on Interweaved TDMA MAC.

- **Broadcast Nature:**
  If node i does not receive an explicit ACK from node $i+1$ before timeout expiry for a DATA frame p it successfully transmitted in the current TDMA time frame, it will unnecessarily retransmit the same frame in the next TDMA time frame, giving rise to bandwidth wastage. Even if it overhears any downstream (nearer to sink)

[1]Interweaved TDMA MAC is an enhancement to basic TDMA MAC, the key difference being that a node commences data transmission once it completes sending an ACK. The time slots of successive nodes overlap - hence the term 'Interweaved'.

node forwarding the same frame (which implicitly acknowledges its successful transmission), it will ignore this information and proceed to retransmission unnecessarily in the next TDMA frame.
In addition, a DATA frame p forwarded by node i will only be processed by its immediate downstream neighbor, i.e., node i+1. Any other downstream node, including the sink, might have overheard the same frame and helped to forward the frame more reliably towards the sink (with fewer hops).

- **Spatial and Temporal Variance:**
The underwater acoustic channel quality can vary spatially (*e.g.* due to varying water depths and topography of the underwater terrain) as well as temporally (*e.g.* due to sea traffic and wind that contributes to ambient noise). As a result, longer links can sometimes experience better conditions than shorter links. Hence, a *strictly* hop-by-hop data delivery scheme may be stalled in the event of a temporal degradation of one of the links.

In recent years, various *opportunistic* ARQ schemes that exploit the broadcast nature via overhearing to improve multihop data delivery in underwater acoustic networks [3], [4] have been proposed. In [4], an *opportunistic* ARQ scheme that uses knowledge of per-hop BER to decide whether to perform implicit or explicit acknowledgement was proposed. The scheme reduces overhead of Stop & Wait ARQ by treating overheard data packets forwarded by downstream nodes as ACK for previously transmitted data, and has been analytically shown to outperform non-*opportunistic* ARQ schemes. However, overhearing is limited to (*i*) a single direction, (*ii*) a single packet type (*i.e.*, data packets), and (*iii*) only from a node's immediate downstream neighbor. In [3], the authors demonstrated the performance improvement that can be achieved by overhearing ACK packets from the whole network.

In this paper, we propose a fully-*opportunistic* Stop & Wait ARQ built on an Interweaved TDMA MAC to improve the performance of multihop data delivery, where nodes leverage on overheard DATA from all upstream (nearer to source) nodes and overheard DATA and ACK from all downstream (nearer to sink) nodes. In other words, overhearing is exploited in both directions, using both DATA and ACK, and is not limited to adjacent neighbors - hence the term *Bidirectional Overhearing*.

The paper is organized as follows: the main features of our proposed fully-*opportunistic* scheme is described in Section II. In Section III, we describe the design specifications of our proposed scheme. Simulation results that illustrate the efficacy of our scheme compared to non-*opportunistic* and semi-*opportunistic* schemes in terms of packet delivery reliability, energy-efficiency and end-to-end delay are shown in Section IV. Finally, we provide some concluding remarks and outline directions for future work in Section V.

II. Opportunistic ARQ with Bidirectional Overhearing

In addition to the *strictly* hop-by-hop (non-*opportunistic*) exchange of DATA and ACK frames, three types of overheard frames are used by the proposed *opportunistic* S&W ARQ with *bidirectional overhearing* on Interweaved TDMA MAC data delivery scheme (DDS), as illustrated in the timing diagram shown in Figure 3.

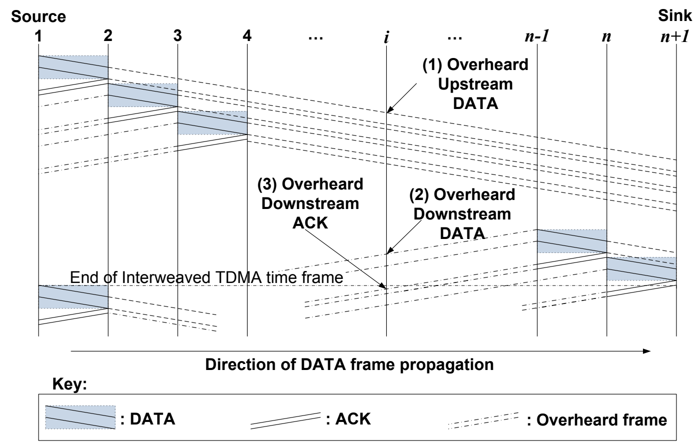

Fig. 3. Timing diagram for the Data Delivery Scheme using a fully-*opportunistic* Stop & Wait ARQ with *Bidirectional Overhearing* on Interweaved TDMA MAC. The 3 types of overheard frames used by the proposed DDS are annotated: (1) Upstream DATA, (2) Downstream DATA, (3) Downstream ACK.

These overheard frames are considered *opportunistic* for the following reasons:

- These frames are not explicitly meant (addressed) for the nodes that overhear them;
- While overhearing such frames can be leveraged upon to improve performance, failure to receive such frames does not cause the scheme to malfunction - in fact, in the worse-case scenario whereby none of the *opportunistic* frames were overheard, the proposed scheme will simply fall back to its hop-by-hop equivalent.

Upstream ACK frames overheard do not provide useful information and are thus not used by the *opportunistic* DDS.

By leveraging on *bidirectional overhearing*, the proposed DDS offers the following advantages compared with non-*opportunistic* schemes:

- **Better Reliability:** With all downstream nodes listening on DATA frames, DATA frames have the opportunity to reach the destination through fewer hops. The lesser a frame is relayed, the lower the probability of it getting dropped along the network due to poor channel conditions. There is a even a chance for the DATA frame to reach the sink in a single-hop with conducive channel conditions;
- **Improved Latency:** DATA frames being able to 'skip' hops *opportunistically* have a chance of arriving at the destination in a shorter time. Also, with the use of

implicit ACK, there are more avenues for terminating unnecessary transmissions and retransmissions. In the event that an explicit ACK is lost, a transmitting node can additionally listen for implicit ACKs as a trigger to terminate its pending retransmission. Furthermore, implicit ACK aids in the purging of duplicate frames in the network layer queues in upstream nodes. This reduces unnecessary transmissions, bandwidth wastage, and aid in the reduction of packet end-to-end delay;

- **Improved Energy-Efficiency:** The reduction in unnecessary transmissions (as frames traverse fewer hops and retransmissions are reduced) across the entire network naturally leads to more energy-efficient data delivery;
- **No Additional Communication Overhead:** Except for a modification in the ACK frame format, the proposed DDS does not create additional network traffic explicitly and hence it can be implemented on other MAC protocols without requiring drastic changes on the medium access interface.

III. Design Specifications

The proposed scheme is implemented using a cross-layer network architecture as illustrated in Figure 4. The interface between user applications and the DDS is adapted from the design in [5], whereby instead of redesigning an entire networking stack, the DDS leverages on the widely-tested TCP/IP protocol stack, using IP packets as the standard exchange format with the upper layers. We now describe the relevant functional blocks for implementing the proposed DDS scheme.

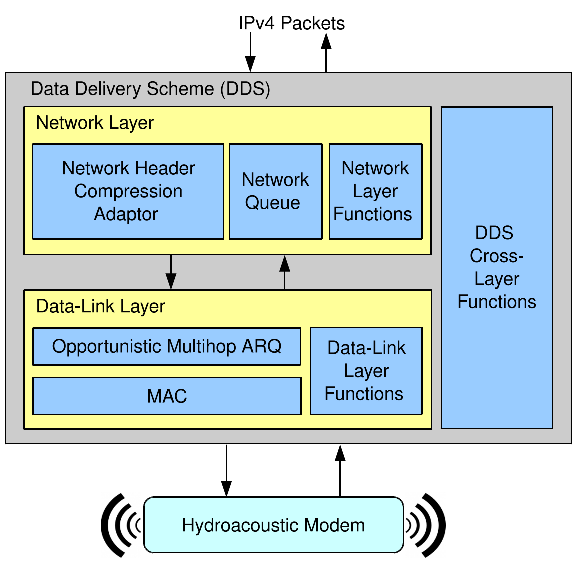

Fig. 4. Cross-layer network architecture of the Data Delivery Scheme (DDS) using *Opportunistic* ARQ with *Bidirectional Overhearing*.

- **Network Header Compression Adaptor:** Due to the very limited bandwidth and data rate of underwater acoustic communications, the authors of [5] proposed the compression of the standard IPv4 headers and reduction in address size to reduce overhead as much as possible. This functional block strips off the IPv4 header and appends to the payload a compressed IP header with the bare minimum fields. The 5-bytes long compressed IP header is shown in Figure 5.
- **Network Queue:** DATA frames, either from an application or an upstream node (relaying) are enqueued in the network queue if the data-link layer is currently busy processing another frame. Note that due to the cross-layer nature of the DDS scheme, the *Opportunistic* Multihop ARQ component can access the network queue through the invocation of cross-layer functions.
- **DDS Cross-Layer Functions:** The DDS cross-layer functions enable the data-link layer access to the compressed IP header of DATA frames and the network queue. The necessary functions are as follows:
GET_NETWORK_INFO: Gives data-link layer access to the compressed IP header of a DATA frame;
NETWORK_DLL_MATCH(SEQ): Searches the network queue and data-link layer for any match of DATA frames with the network sequence number SEQ;
NETWORK_DLL_REMOVE(SEQ): Removes from the network queue or data-link layer the DATA frame matching network sequence number SEQ;
- **Opportunistic Multihop ARQ:** The key intelligence of our proposed scheme resides in this functional block, whereby decisions to process, queue or discard overheard DATA & ACK frames are made. The algorithms will be discussed in the following section.
- **MAC:** The Interweaved TDMA MAC protocol used in the proposed DDS is implemented in this functional block. As mentioned, the DDS scheme may also be used in conjunction with other MAC protocols. This can easily be accomplished by replacing the TDMA MAC with the desired MAC protocol.

A. Frame Formats

Figure 5 shows the DATA and ACK frame formats described in [5]. This ACK frame format is not sufficient for our proposed DDS as it only carries the sequence number at the data-link layer that is useful only as an explicit ACK to the node's immediate upstream neighbor. Moreover, the upstream or downstream nature of the DATA frame it is acknowledging for cannot be established with certainty.

Hence, we propose a modified ACK frame format as illustrated in Figure 6. The 1-byte data-link layer sequence number is replaced by a 2-bytes network layer sequence number. Additionally, the network ACK frame contains the network source and destination (sink) address of the DATA frame it is acknowledging for. This allows any node overhearing the network ACK frame to differentiate between an upstream or downstream ACK relative to itself.

The 'Receiver Address' field serves the same function as the original ACK frame in Figure 5, storing the address of the node that the ACK frame is explicitly meant for. In other words, for an ACK frame sent by node $i+1$ in response to

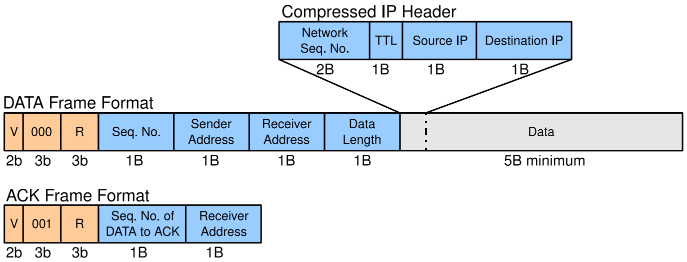

Fig. 5. DATA & ACK frame formats. The 1-byte long sequence number in the ACK frame is only relevant at the data-link layer and therefore cannot be used for implicit acknowledgements. Also shown is the compressed IP header that is part of the data payload.

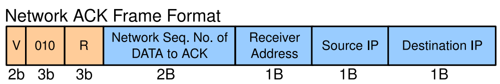

Fig. 6. Network ACK frame format. This modified ACK frame allows for implicit acknowledgements by matching the 2-bytes long network layer sequence number.

a DATA frame received from node i, the 'Receiver Address' field will hold the address of node i.

B. Algorithms for Opportunistic ARQ with Bidirectional Overhearing

For a node i as shown in Figure 1, the rules of the proposed scheme upon receipt of a DATA frame p and network ACK are given in Algorithm 1 and 2 respectively.

Algorithm 1 Pseudocode for receipt of DATA frame p

```
procedure RECV_DATA(p)
    GET_NETWORK_INFO(p)
    if (Sender = Node i − 1) then
        Send ACK
    end if
    if (Node i = SINK) then
        Pass p to application
    else
        MATCH = NETWORK_DLL_MATCH(SEQ)
        if (SENDER = Node 1 to i − 1) then
            if (MATCH) then
                Discard p
            else
                Enqueue p
            end if
        else                    // SENDER = Node i + 1 to n
            if (MATCH) then
                NETWORK_DLL_REMOVE(SEQ)
            end if
        end if
    end if
end procedure
```

We demonstrate the key features of Algorithms 1 and 2 for a 5-node, 4-hop network using the timing diagram in Figure 7, where the source node transmits a single DATA frame p. Lost data and ACK frames are denoted by an 'X' mark. The figure illustrates the following sequence of events:

Algorithm 2 Pseudocode for receipt of network ACK

```
procedure RECV_ACK(ACK)
    if (Sender = Node i + 1) then
        Remove acknowledged DATA from data-link
    else
        MATCH = NETWORK_DLL_MATCH(SEQ)
        if (Sender = Node i + 2 to n + 1) then
            if (MATCH) then
                NETWORK_DLL_REMOVE(SEQ)
            end if
        else                  // SENDER = Node 2 to i − 1
            Do nothing          // upstream ACK not used
        end if
    end if
end procedure
```

1) Node 1 transmits DATA frame p to node 2, which was received by node 2 and overheard as upstream DATA at node 3.
2) In response, node 2 transmits a network ACK to node 1 but frame was lost. Similarly, when it was node 2's time slot to transmit frame p, that transmission en route to node 1 was lost. It was however received by node 3, which discarded the received frame since a search of its data-link layer and network queue showed that it already was in possession of an identical DATA frame received previously from node 1.
3) Node 3's transmission of frame p was overheard as downstream DATA by node 2. This acted as an implicit acknowledgement, terminating the pending retransmission attempt at node 2. Node 5 overheard frame p from node 3, and since node 5 was the network destination of p, p was passed up to the application layer. Frame p traversed 2 hops from the source to the sink.
4) Node 4's network ACK to node 3 was overheard as downstream ACK by node 1. This acted as an implicit acknowledgement, terminating the pending retransmission attempt at node 1.

IV. Performance Evaluation

The proposed data delivery scheme (DDS) - *Opportunistic* S&W ARQ with *bidirectional overhearing* built on an Interweaved TDMA MAC was implemented and the performance evaluated via simulations on the Qualnet Network Simulator [6]. The performance metrics used for comparison are: (*i*) packet delivery ratio (PDR), (*ii*) average network energy consumption per delivered packet and (*iii*) average delay (end-to-end) per delivered packet.

In order to determine the contribution of overhearing each frame type to the performance of the proposed DDS, the simulation results are presented for (*i*) fully-*opportunistic* ARQ

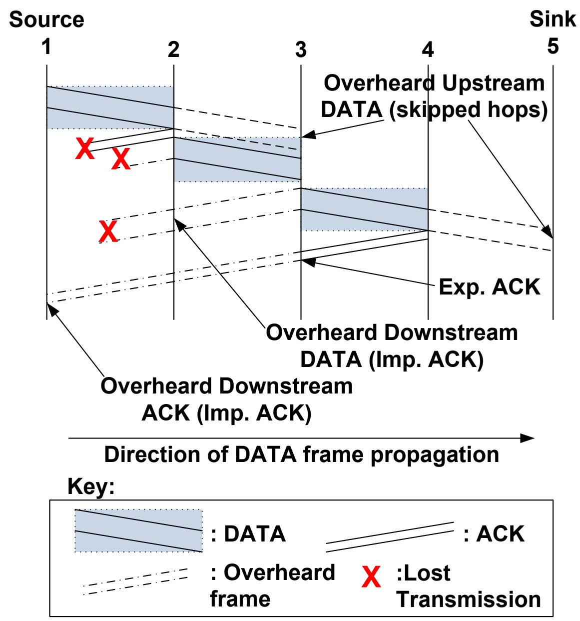

Fig. 7. Timing diagram of hypothetical transmission of a single DATA frame p across a 4-hop network.

with *bidirectional overhearing*, (*ii*) semi-*opportunistic* ARQ with overhearing for downstream DATA & ACK (implicit ACK) only, (*iii*) semi-*opportunistic* ARQ with overhearing for upstream DATA only and (4) non-*opportunistic strictly* hop-by-hop ARQ.

A. Simulation Parameters

The simulated network comprises n+1 nodes arranged in a linear topology, as illustrated in Figure 1, with adjacent nodes spaced 1000 metres apart, and nodes 1 and n+1 configured as source and sink nodes respectively. Simulations for each of the above-mentioned fully-*opportunistic*, semi-*opportunistic* and non-*opportunistic* ARQ schemes were ran for different-sized networks, varying from n=2:11, for performance comparison.

In each simulation, a constant bit-rate generator (CBR) was used at the application layer of the source node, generating and passing to the DDS 1000 DATA packets at a rate of one packet per second. A 58-bytes long DATA payload was generated by the CBR such that the resulting DATA frame at the data-link layer inclusive of headers was 64-bytes long. All nodes were configured to retransmit each DATA frame up to a maximum of 5 times before dropping the frame, and the simulation will terminate when all DATA frames are either delivered to the sink or dropped.

An underwater channel model based on [2] was implemented and used for all acoustic signal transmissions under our simulation model. Although impossible to fully represent the true characteristics of the transmission channel in simulations, the model takes into account path-loss, ambient noise and propagation delays to provide realistic settings as much as possible.

Each performance metric is obtained by averaging the simulation results over 10 trials (using different seed values) and are plotted in Figures 8, 9 and 10.

B. Simulation Results & Analysis

Packet Delivery Ratio: The packet delivery ratio (PDR) or reliability performance of the different schemes are presented in Figure 8. The PDR of the non-*opportunistic* hop-by-hop ARQ with no reliability is plotted to show the beneficial effects of retransmissions at the data-link layer.

The fully and semi-*opportunistic* ARQ schemes using *bidirectional overhearing* and overhearing of upstream DATA show significantly better packet delivery as compared to their non-*opportunistic* counterpart, delivering 88% and 97% more packets respectively over a 10-hop network.

It is observed that, as expected, overhearing of implicit acknowledgement frames does not improve the reliability of data delivery over the original scheme that only relies on explicit ACK. However, schemes that exploit overhearing of upstream DATA packets achieve higher reliability as DATA packets are now given the chance to travel further than just the immediate downstream neighbor, reducing the number of relays while at the same time increasing redundancy, thus reducing the likelihood of packet drop. Since the usage of implicit acknowledgement reduces duplicate DATA packets in *bidirectional overhearing*, increased reliability attributed to redundancy is reduced compared to the scheme that overhears upstream DATA packets only.

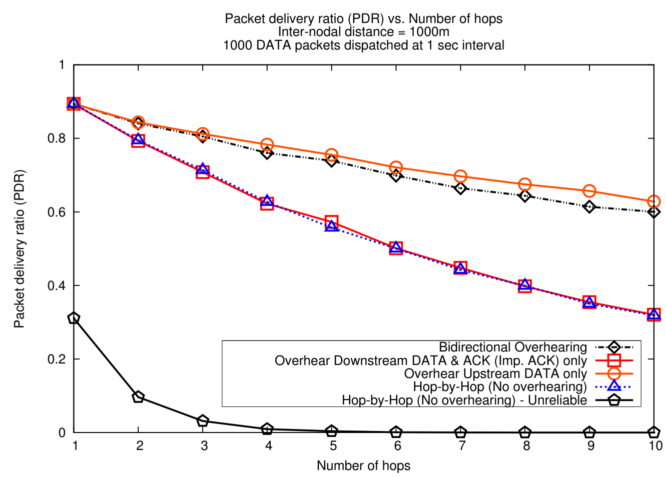

Fig. 8. Simulation results of packet delivery ratio (PDR) plotted against the number of hops. A maximum retransmission of 5 was used by all schemes except Hop-by-Hop - Unreliable, which transmits each DATA frame a maximum of 1 time. This reflects both the adverse conditions of the channel model and the beneficial effects of retransmissions.

Energy-Efficiency: A simple energy consumption model was used for the evaluation of energy-efficiency of each of the schemes, whereby the energy cost for transmission is defined as the size of the frame, and that for reception to be half of the former. The total energy consumption of the network per successfully delivered DATA packet was then plotted for all schemes and is shown in Figure 9.

The gain in energy-efficiency with *bidirectional overhearing* as compared to just overhearing in a single direction or none at all is evident, with *bidirectional overhearing* achieving a 43% reduction in energy consumption compared to its non-*opportunistic* counterpart. This is despite the usage of a longer ACK frame that consumes more energy. Without overhearing, the energy consumption is the highest as all DATA packets have to travel hop-by-hop to reach its final destination. All overheard DATA and ACK frames are processed but not used in any way. With overhearing of implicit acknowledgements, the energy consumption is higher than that for the overhearing of upstream DATA . This result seems unintuitive since implicit acknowledgement packets help in reducing duplicates and purging queues, and should result in a reduction in total energy consumption. However, this can be explained by the fact that overhearing of downstream DATA and ACK packets only serve to reduce retransmissions and duplicates but not help in making packets traverse fewer hops. In other words, packets still have to traverse on a hop-by-hop basis.

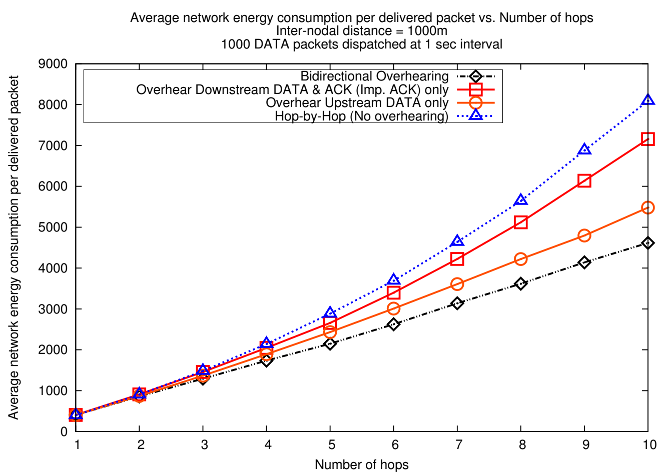

Fig. 9. Simulation results of average network energy consumption per delivered packet plotted against the number of hops. A simple energy consumption model was used, whereby the energy cost for transmission is defined as the size of the frame, and that for reception to be half of the former.

Packet Latency: Figure 10 shows the plot of average end-to-end delay per delivered packet. The scheme with *bidirectional overhearing* reaps an 8% improvement in end-to-end delay per delivered packet as compared to its non-*opportunistic* counterpart. It is observed that with the usage of implicit acknowledgements (the overhearing of downstream DATA & ACK frames) which leads to the removal of duplicate DATA packets and purging of network queues, average delay per delivered packet is improved. This is the case for both *bidirectional overhearing* and overhearing of downstream DATA & ACK only, performing the best in terms of delay. However, the delay performance for the scheme overhearing DATA packets only is slightly worse than the case without overhearing. This is again expected as the overhearing of DATA frames introduces duplicates of frames along the network, lengthening queues and in turn increasing the queuing delays at each of the nodes.

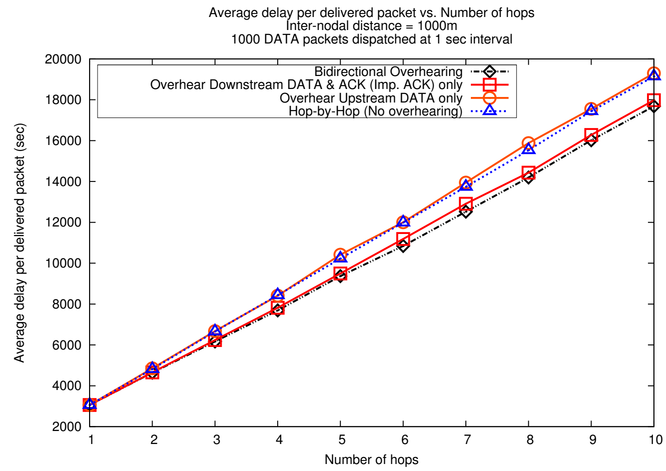

Fig. 10. Simulation results of average delay per delivered packet plotted against the number of hops. Delay is derived from the time difference between dispatch and receipt at the application layer of the source and sink node.

V. Conclusion and Future Work

In this paper, we proposed a multihop data delivery scheme using a fully-*opportunistic* ARQ with *bidirectional overhearing*, whereby nodes leverage on the broadcast nature of acoustic channels and their spatial and temporal variance to overhear (*i*) data packets from all upstream (nearer to source) nodes to speed up data delivery and (*ii*) data & acknowledgement packets from all downstream (nearer to sink) nodes as implicit acknowledgements. We performed simulation studies to evaluate the performance of the proposed scheme and showed that the fully-*opportunistic* S&W ARQ with *bidirectional overhearing* outperforms its non-*opportunistic* or semi-*opportunistic* counterparts in terms of reliability, energy-efficiency and latency. In the future, we plan to implement and test the performance of the scheme on contention-based MAC protocols such as ALOHA and slotted ALOHA. In addition, we also plan to implement the scheme on acoustic modems, and evaluate its actual performance in sea trials.

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