A Multi-hop ARQ Protocol for Underwater Acoustic Networks

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***Abstract*— Underwater acoustic networks are envisaged to be the enabling technology for oceanographic data collection, pollution monitoring, offshore exploration and tactical surveillance applications. Unique characteristics of underwater acoustic channels such as large propagation delays and high bit error rates pose a challenge to designing reliable and efficient communication protocols. In this paper, we propose an opportunistic acknowledgement scheme suited for Stop and Wait ARQ protocols and demonstrate using simulations that it achieves better latency and energy efficiency than traditional non-opportunistic schemes for both one and two-dimensional multi-hop acoustic channels.**

I. Introduction

Many applications have been envisaged for underwater sensor networks, including seismic monitoring, tactical surveillance and equipment monitoring and fault detection. To realize these applications, we may borrow many design principles and tools from ongoing, ground-based terrestrial sensor research. Acoustic communication is a promising candidate for underwater communication since radio is not suitable for underwater usage because of extremely limited propagation. However, there exist some fundamental differences between the radio and acoustic media, e.g., (a) long and variable propagation delay and (b) high and variable bit error rate (BER) in the latter that pose research challenges in underwater sensor networking [1], [2].

In a typical underwater sensor network, sensor nodes are interconnected via wireless links to one or more underwater *sinks* that are responsible for reliably relaying data to a surface station. While direct communication between sensor and sink nodes (long range, high power) is simple, *multi-hop* (short-range, low power) communication using complex protocols may be necessary, for example, in military surveillance applications, where operational covertness and low power consumption are critical requirements.

To establish reliable multi-hop communication, an automatic repeat request (ARQ) procedure is required to manage the retransmission of erroneously received / lost data packets. Since current acoustic modem technology typically supports half-duplex mode, the method of choice for current ARQ implementations is the simple Stop and Wait (S&W) protocol where each transmitted packet has to be *acknowledged* before the next packet can be transmitted. This can be simply achieved by *explicitly* transmitting an acknowledgement packet (typically of much smaller size than data packet) per successfully received data packet in a *single-hop* link.

However, in a multi-hop channel, due to the broadcast nature of the medium, if a node transmits a packet and hears its next-hop neighbour transmitting it forward, it is an *implicit* acknowledgement that the packet has been successfully received by its neighbour, hence nullifying the need for explicit acknowledgement. While this may be more *efficient* (e.g. in terms of bits transmitted per data packet and/or waiting time for acknowledgements) than explicit acknowledgement in terrestrial wireless links with very low BER, it may not be so for acoustic links with substantially higher BER. In addition, while acknowledgement may be implemented on a per-hop or end-to-end basis, the former is expected to be more efficient for high BER acoustic links.

Hence, in this paper, we propose a per-hop hybrid implicit/explicit acknowledgement scheme for S&W ARQ in a multi-hop acoustic channel, and demonstrate its efficacy in one- and two-dimensional architectures suitable for long range, underwater surveillance applications.

II. Related Work

Variants of S&W have been proposed [3], [4], [5], [6] for single-hop communication links to improve its efficiency by transmitting *blocks* of packets, rather than a single packet, thus making better utilisation of the time spent in waiting for the acknowledgements. However, to the best of our knowledge, ARQ mechanisms for multi-hop communication is much less studied [7], [8].

Recently, in [9], the author conducted a statistical analysis of protocol efficiency for a class of S&W protocols, leading to an optimal packet size in terms of hop-length, bit rate and expected BER under typical underwater channels. As in [3], [4], [5], [6], this work considers S&W schemes based on transmitting groups of packets for which selective acknowledgements are generated. A similar analysis was conducted in [10], which additionally accounted for cross-layer interactions with medium access control layers and forward error correction. However, the above analyses were conducted over *single-hop* acoustic links.

On the other hand, *multi-hop end-to-end* ARQ (e2e-ARQ) concepts (as opposed to S&W which is a per-hop (PH-ARQ) mechanism) were proposed recently in [7], [8] primarily to

handle node mobility in beyond 3G terrestrial access networks. An e2e *RelayARQ* protocol is proposed in [7] that allows relay or intermediate nodes to seamlessly "leave and join" without breaking the end-to-end connection by maintaining a common protocol state between all nodes. A multi-hop ARQ mechanism (*M-ARQ*) is proposed in [8] by coupling a PH-ARQ protocol with an e2e-ARQ. Although e2e-ARQ protocols may perform better in terms of reliability and efficiency than PH-ARQ, the added complexity may not be suited for implementation in underwater networks comprising energy-starved sensor nodes. In addition, node mobility may not be a critical issue in underwater networks. Therefore, we focus our efforts on devising a S&W protocol suited for multi-hop communication in underwater networks.

III. Stop and Wait ARQ for multi-hop acoustic communication

A. System Model and Problem Definition

Consider an *n*-hop acoustic channel comprising a source node, sink node and *n*-1 relay nodes as shown in Fig. 1(a). One of the distinguishing features of underwater acoustic communication is *spatially-varying* channels, which is characterized here by the BER along each hop *j*, p_j.

When a packet of b bits is transmitted over hop j, the corresponding packet error probability $p_j(b)$, is:

$$p_j(b) = 1 - (1 - p_j)^b.$$

The time required for this packet to arrive at its intended recipient node (either node j-1 or j+1) comprises the *transmission* delay $t = b/r$ and the *propagation* delay, $t_P = l/c$, where r is the transmission rate of the channel, l is the hop-length (m) and c is the speed of sound (m/s).

We consider two types of packets in this study, namely data packets of b_D bits and acknowledgement (ACK) packets of b_A ($<< b_D$) bits each, with transmission times given by $t_D = b_D/r$ and $t_A = b_A/r$ respectively.

B. Stop and Wait (S&W) ARQ

With S&W ARQ, the transmitter sends a packet and waits for the acknowledgment. Once it arrives, the transmitter moves on to a new packet; otherwise, if it does not arrive within a pre-specified duration, called the *time-out*, the packet is retransmitted. Due to the high BER of acoustic channels, the acknowledgement may be lost and this will trigger an unnecessary retransmission after the time-out. To reduce unnecessary transmission (hence, *energy* consumption) of data packets which have already been received, we apply the following rule to all acknowledgement schemes considered in this study:

Rule 1: Whenever a *relay* node *j* receives a packet from node *j*-1, it transmits an ACK packet if its previous data transmission is already acknowledged. On the other hand, (*non-relay*) node 1 (*n*+1) only transmits data (ACK) packets.

The design of the acknowledgement procedure is important since, in addition to *energy*-efficiency, it also determines the *latency*-efficiency of the ARQ mechanism, where a longer waiting time before the next packet can be transmitted indicates lower efficiency. The acknowledgement procedure can be done *implicitly* through the data packet itself or *explicitly* through an ACK packet. These mechanisms will be described in the subsequent sections.

*1) Implicit Acknowledgement (*IMP*):* Consider the transmission of a data packet (b_D bits) over hop j from node j to node j+1. Since the transmission is isotropic, this packet may also be received at node *j*-1 and serve as an *implicit* ACK for its transmission. The corresponding packet error probability over hop *j*-1 (or probability of unsuccessful acknowledgment for node *j*-1's transmission) is:

$$p_{j-1}(b_D) = 1 - (1 - p_{j-1})^{b_D}.$$

If node *j*-1 is not acknowledged after a time-out interval, $\tau_{O,\text{IMP}}$=2(t_P+t_D), it retransmits the data packet. We denote this ARQ scheme by IMP.

*2) Explicit Acknowledgement (*EXP*):* Since acoustic channels are characterized by high BER, a substantial proportion of implicit ACK packets may be erroneously transmitted, triggering retransmission of data packets that consumes energy and hence should be minimized. One way to achieve this is to define an *explicit* ACK protocol (EXP) that piggybacks the ACK packet to each data packet. In this way, the corresponding probability of unsuccessful acknowledgment for node *j*-1's transmission is reduced to:

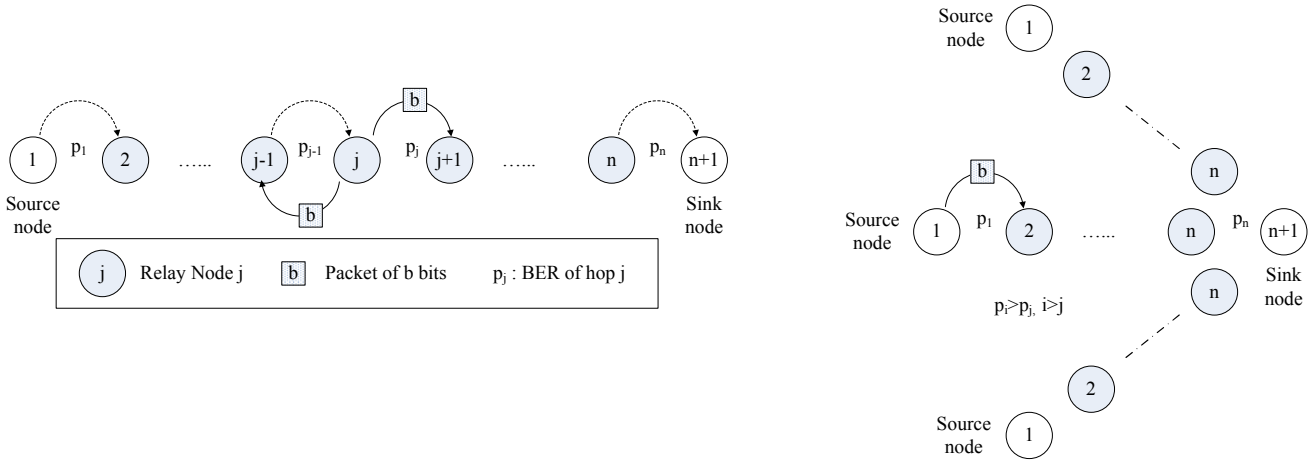
$$p_{j-1}(b_A) = 1 - (1 - p_{j-1})^{b_A}.$$

However, the corresponding time-out interval is increased to $\tau_{O,\text{EXP}}$=2(t_P + t_D + t_A). Although the improvement in the likelihood of successful acknowledgment comes at the expense of longer time-out intervals, the relative performance of IMP and EXP in terms of latency- and energy-efficiency depends on the choice of system parameters.

Hence, our objective in this study is to design an acknowledgement scheme for S&W ARQ that *maximizes* the latency-efficiency and/or energy-efficiency (i.e. *minimizes* the energy consumption) for data delivery in a multi-hop acoustic communication system. Quantitatively, for the delivery of a single data packet from node 1 to node n+1 for the system shown in Fig. 1(a), we evaluate the delivery time (T_d), total time required for all transmissions to cease (T_c) and the total number of bits transmitted (B). The metric T_c measures the latency-efficiency while B measures the energy-efficiency of the acknowledgement scheme.

IV. Opportunistic Acknowledgement Schemes for multi-hop acoustic communication

To determine an optimally-efficient acknowledgement scheme, it is necessary to obtain analytic expressions for each metric in terms of the channel parameters. While it is straightforward to derive the packet delivery time T_d analytically for a multi-hop communication system, it is complex to do so for (T_c, B). Hence, we assume that the latter quantities may be approximately minimized by minimizing the corresponding per-hop quantities.



(a) One-dimensional *n*-hop acoustic channel

(b) Two-dimensional multi-hop acoustic sensor network

Fig. 1. (a) Illustration of Stop and Wait (S&W) ARQ mechanism over a one-dimensional *n*-hop communication channel, where p_j is the BER over the jth hop and (b) Extension to two-dimensional multi-hop network with single sink, where $p_i > p_j$, $i > j$.

Let us assume that a *new* packet has just been received successfully at node j+1 from node j. With S&W ARQ, the above event has to be acknowledged at node j before it can transmit the next packet. We quantify the per-hop latency-efficiency and energy-efficiency by the *expected* time elapsed and number of bits transmitted between node j and j+1 until node j has been acknowledged. We denote these quantities by $t_{j,\text{A}}$ and $b_{j,\text{A}}$ for acknowledgement scheme A respectively.

A. Latency-efficient Opportunistic Acknowledgement

Based on the mechanisms of IMP and EXP, we obtain the expressions for $t_{j,\text{IMP}}$ and $t_{j,\text{EXP}}$ as follows:

$$\begin{aligned} t_{j,\text{IMP}} &= \frac{\tau_{O,\text{IMP}}}{2}\frac{1+p_j^2(b_A)}{1-p_j^2(b_A)} + [t_D + t_A + 2t_P]p_j(b_D), \\ t_{j,\text{EXP}} &= \frac{\tau_{O,\text{EXP}}}{2}\frac{1+p_j^2(b_A)}{1-p_j^2(b_A)} - t_D p_j(b_A). \end{aligned}$$

Hence, over hop j, we expect the IMP scheme to perform better in terms of latency-efficiency if the following condition holds:

$$t_{j,\text{IMP}} < t_{j,\text{EXP}}.$$

If we assume that $p_j(b) \approx b \cdot p_j$ and $p_j^2(b_A) << 1$ (valid for p_j <<1), the above condition can be expressed in a simple form as follows:

$$p_j < \frac{t_A}{(t_D + t_A + 2t_P)b_D + t_D b_A} \equiv p_l^*. \tag{1}$$

Based on Eq. (1), we propose an opportunistic acknowledgement scheme, HYB-LAT, that exploits the spatial variance of acoustic channels to improve latency-efficiency using the following rule:

Rule 2: Whenever a relay node *j*+1 receives a packet from node *j*, it operates according to the following:

$$\begin{aligned} &\text{If} \quad p_j \geq p_l^*, && \text{node } j\text{+1 performs EXP;} \\ &\text{else} && \text{node } j\text{+1 performs IMP.} \end{aligned}$$

B. Energy-efficient Opportunistic Acknowledgement

As in Section IV-A, we can obtain the expressions for $b_{j,\text{IMP}}$ and $b_{j,\text{EXP}}$ as follows:

$$\begin{aligned} b_{j,\text{IMP}} &= \frac{b_D + b_D[p_{j-1}(b_D) - p_j(b_A)] + b_A p_j(b_D)}{1 - p_j(b_A)}, \\ b_{j,\text{EXP}} &= \frac{b_D + b_A[1 + p_j(b_A) - p_j^2(b_A)]}{1 - p_j(b_A)}. \end{aligned}$$

Hence, we expect the IMP scheme to be more energy-efficient over hop j if the following condition holds:

$$b_{j,\text{IMP}} < b_{j,\text{EXP}}.$$

Using the same assumptions as in Section IV-A, the above condition can be expressed in terms of the system parameters as follows:

$$p_j < \frac{b_A}{b_D^2 - b_A^2} \equiv p_e^*. \tag{2}$$

Using Eq. (2), we propose another opportunistic acknowledgement scheme, HYB-ENE, that improves energy efficiency using the following rule:

Rule 3: Whenever a relay node *j*+1 receives a packet from node *j*, it operates according to the following:

$$\begin{aligned} &\text{If} \quad p_j \geq p_e^*, && \text{node } j\text{+1 performs EXP;} \\ &\text{else} && \text{node } j\text{+1 performs IMP.} \end{aligned}$$

C. Illustration of Opportunistic Acknowledgement Schemes

To illustrate the operating region of our proposed opportunistic acknowledgement schemes over any hop, we consider a multi-hop acoustic communication channel with system parameters as given in Table I.

System parameters (bits)	Value
b_D (kbits)	1-4
b_A (kbits)	b_D/20
c (m/s)	1500
l (m)	200
r (kbps)	5-7

TABLE I

Parameters to illustrate and evaluate the performance of Stop and Wait ARQ protocols over the multi-hop acoustic systems in Fig. 1.

Using Eq. (1) and (2), we plot (p_l^*, p_e^*) against b_D in the LHS of Fig. 2. We observe that $p_e^* > p_l^*$, and we can identify three operating regions in terms of (b_D, p_j) described as follows:

- **RI: Apply IMP**
  In this region, the opportunistic acknowledgement scheme selects IMP to achieve better performance in terms of *both* latency- and energy-efficiency.
- **RII: Apply EXP**
  In this region, the opportunistic acknowledgement scheme selects EXP to achieve better performance in terms of *both* latency- and energy-efficiency.
- **RIII: Trade-off between latency and energy-efficiency**
  In this region, the preferred acknowledgement scheme depends on the relative importance of latency- and energy-efficiency. If the objective is to improve latency-efficiency, EXP should be applied; otherwise, IMP should be applied for better energy-efficiency.

V. Numerical Results

We compare the performance of our proposed opportunistic acknowledgement schemes against the traditional non-opportunistic IMP and EXP schemes for S&W ARQ in terms of (T_d, B, T_c) for the multi-hop acoustic communication systems in Fig. 1 using the parameters defined in Table I.

A. Spatially-invariant channel

We consider a one-dimensional n-hop acoustic channel that is suitable for long-range sensing / surveillance applications, as shown in Fig. 1(a). We assume that the channel is spatially-*invariant* (i.e., BER $p_j = p$), simulate the delivery of a single data packet (b_D Kbits) and evaluate (T_d, B, T_c) averaged over 10000 runs.

To demonstrate the effectiveness of our proposed opportunistic acknowledgement schemes, we consider $5\times10^{-6}\leq p\leq 5\times10^{-5}$ which is within the typical interval [10^{-6}, 10^{-2}] [11] for acoustic channels and also includes (p_l^*, p_e^*) as given in the LHS of Fig. 2.

The results obtained for n=6 and b_D = 2 Kbits are shown in the RHS of Fig. 2 and Fig. 3, alongside the corresponding values of (p_l^*, p_e^*) used by the HYB-LAT and HYB-ENE schemes respectively.

As expected, the performance of each scheme is degraded as the channel quality is worsened. For B and T_c, we observe that there exists a *crossover* point (denoted by p^*) for which IMP outperforms EXP when channel conditions are better ($p < p^*$) and vice versa. Since HYB-LAT and HYB-ENE select IMP when channel conditions are better and EXP otherwise, optimal performance can be achieved with HYB-LAT (HYB-ENE) if $p_l^* = p^*$ ($p_e^* = p^*$). In fact, we observe that $p_l^* \approx p^*$ and therefore, HYB-LAT gives the *best* performance in terms of (B, T_c) for the range of channel conditions considered.

On the other hand, such a crossover point does not exists for the metric T_d, and IMP delivers the packet within a shorter duration than EXP under all channel conditions. This is expected since T_d depends only on the per-hop transmission and propagation delay and is *independent* of the acknowledgement scheme employed. Since an ACK packet is piggy-backed to each data packet with EXP, it incurs a larger transmission delay (t_D+t_A) compared with IMP (t_D) and therefore, each packet will be delivered quicker with IMP. Hence, while HYB-LAT also gives the best performance in terms of T_d when channel conditions are good, there is a trade-off between the metrics T_d and (B, T_c) when channel conditions worsen.

B. Spatially-variant channel

Next, we consider a more realistic spatially-*variant* (i.e., $p_i \neq p_j$) one-dimensional n-hop acoustic channel, where p_j is *uniformly* distributed in the interval [p-0.4$\times10^5$, p+0.4$\times10^5$], where p is the mean BER over the n-hops. The corresponding results of Fig. 3 for the spatially-invariant *random* channel are plotted in Fig. 4.

Finally, we extend the one-dimensional string topology in Fig. 1(a) to two dimensions, where several one-dimensional multi-hop communication channels converge to a common sink to form a two-dimensional network, as shown in Fig. 1(b). With such a topology, the channel quality is likely to degrade towards the sink due to convergence of data delivery near the sink. Accordingly, we define a suitable spatially-*variant linear* channel model with mean BER over the channel of p as follows:

$$p_j = p + 0.2 \times 10^{-5} \cdot (j - \lceil \frac{n}{2} \rceil).$$

The corresponding results for the spatially-variant linear channel are plotted in Fig. 5. Similar trends are observed between the spatially-invariant and spatially-variant channels (both random and linear), with the HYB-LAT acknowledgement scheme giving the best performance amongst all the schemes considered.

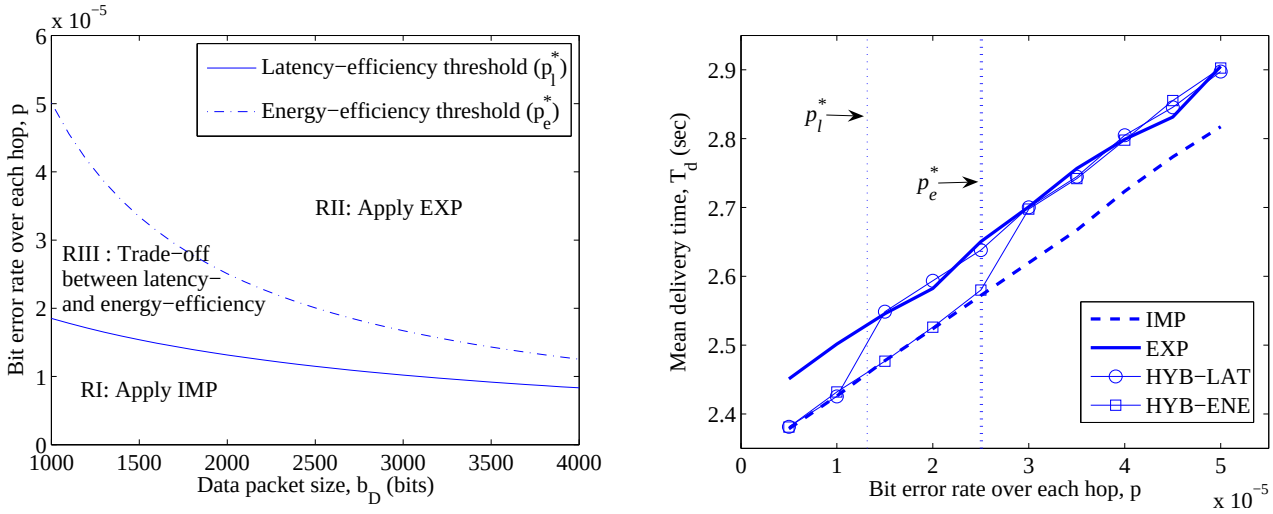


Fig. 2. Operating region (b_D, p_j) of opportunistic acknowledgement schemes HYB-LAT and HYB-ENE (left) obtained for the system parameters in Table I; Mean packet delivery time, T_d under a spatially-invariant channel for n=6 and b_D = 2Kbits (right).

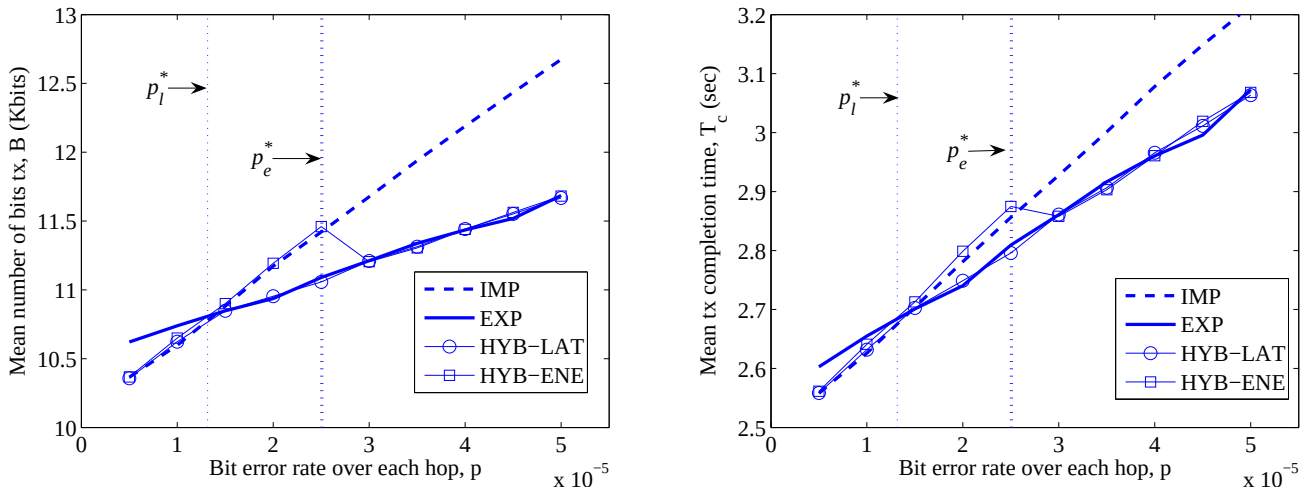


Fig. 3. Mean number of bits transmitted, B (left) and transmission completion time, T_c (right) for a spatially-invariant channel for n=6 and b_D = 2Kbits.

VI. Conclusions and Future Work

Underwater acoustic networks are envisaged to be the enabling technology for oceanographic data collection, pollution monitoring, offshore exploration and tactical surveillance applications. Although reliable and efficient communication protocols are in place for terrestrial networks, they cannot be directly employed in underwater environment due to the unique characteristics of underwater acoustic channels such as higher bit error rates and larger propagation delays. As a result, packet losses are significant, and the design of efficient ARQ schemes to ensure reliability through packet retransmissions and acknowledgements is important.

In this paper, we proposed an opportunistic acknowledgement scheme suited for Stop and Wait ARQ protocols and demonstrated using simulations that it can offer better latency and energy efficiency than traditional non-opportunistic schemes for both one and two-dimensional multi-hop acoustic channels.

While we have considered single packet transmissions in this study, the opportunistic acknowledgement scheme may be applied for transmission of a group of packets [9] to achieve better performance. In addition, we also plan to incorporate this scheme for the comparison of a single path routing scheme with ARQ and a multi-path redundancy routing scheme for the virtual sink architecture proposed in [12].

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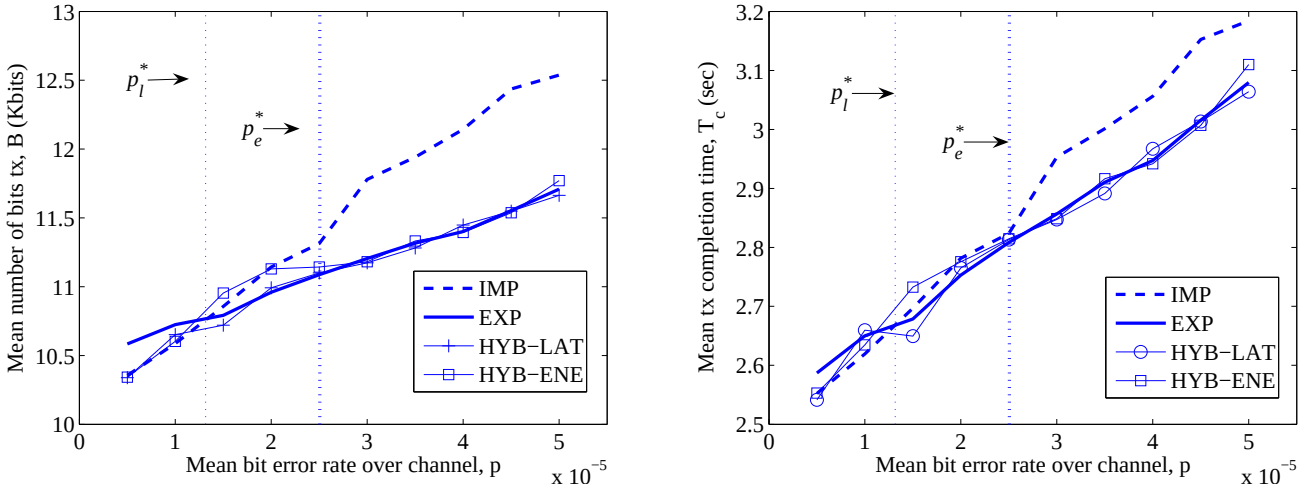

Fig. 4. Mean number of bits transmitted, B (left) and transmission completion time, T_c (right) for a spatially-variant random channel (mean BER = p) for n=6 and b_D = 2Kbits.

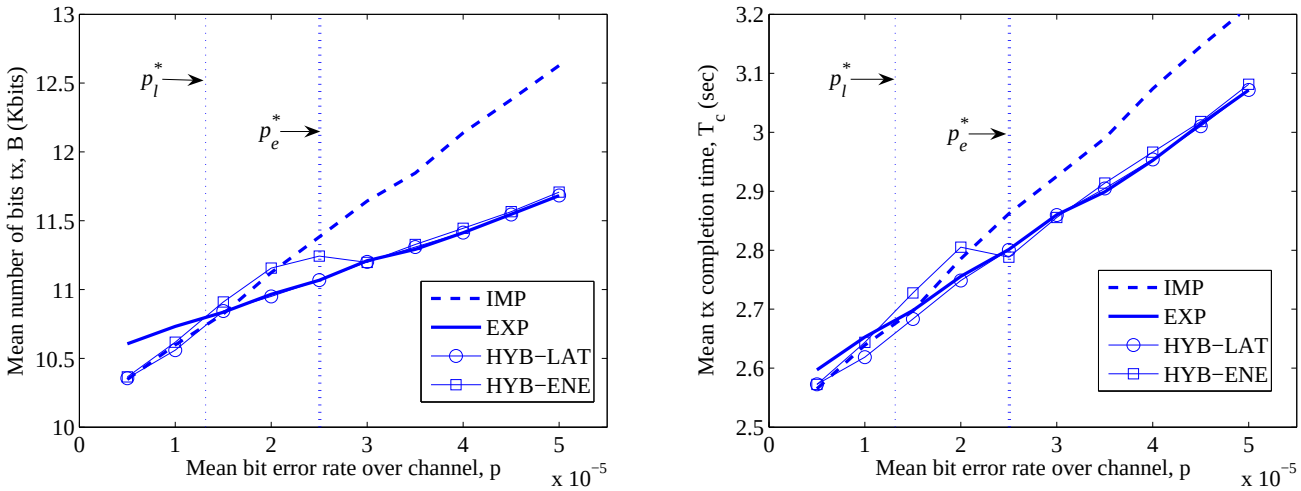

Fig. 5. Mean number of bits transmitted, B (left) and transmission completion time, T_c (right) for a spatially-variant channel (mean BER = p) for n=6 and b_D = 2Kbits.

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