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An Efficient ARQ for Multi-Hop Underwater Acoustic Channel with Long Propagation Delay and High Bit-Error Rate

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Abstract

In the underwater communications, the acoustic channel is in poor communication conditions, such as long propagation delay, narrow bandwidth, and high bit-error rate. For these bad acoustic channels, we propose an efficient automatic repeat request (ARQ) for multi-hop underwater network by using the concepts of concurrent bi-directional transmission, multiple sub-packets, and overhearing data packet instead of the acknowledgement signal. Our results show that the proposed ARQ significantly reduces the transmission latency especially in high BER compared with the existing Stop and Wait ARQ.

Keywords: *Automatic repeat request (ARQ), Muti-hop, Underwater sensor network, Long propagation delay, High bit-error rate*

Subject classification: *Acoustic Communication (6.5)*

I. Introduction

Underwater acoustic sensor networks (UW-ASNs) have been developed for various applica-tions such as environmental monitoring, undersea exploration, disaster prevention, and military purposes. The underwater acoustic channel is significantly different from the terrestrial radio channel in terms of long propagation delay and narrow bandwidth. Also, it has a high bit-error rate (BER) due to the features of large path loss, multi-path fading, time-varying condition, and Doppler spread [1].

To establish a reliable underwater communi-cation link despite these bad channel conditions, an automatic repeat request (ARQ) procedure is required to retransmit the error packets at the data link layer. Among the various ARQ schemes, Stop and Wait (S&W) protocol in which a sender has to wait an acknowledgement for previous packet transmission from a receiver before transmitting the next packet, has been intensively studied as a solution for underwater communication in which current acoustic modems typically operate in half-duplex transmission mode [2-4]. To improve the efficiency of S&W ARQ protocol in terrestrial communication, some schemes transmit a block of packets at one time so that the time spent in waiting for the ackno-wledgement is reduced [5-8]. However, S&W protocol has an excessively long latency in the acoustic channel due to the long propagation delay and high BER. Thus, new efficient ARQ schemes have been required for UW-ASNs.

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In this paper, we propose a latency-improved ARQ protocol for multi-hop UW-ASNs with long propagation and a high BER. We introduce the concepts of the concurrent bi-directional transmission, the multiple sub-packets, and the backward-overhearing data packet instead of the acknowledgement (ACK) signal. These allow a reduction in power consumption and transmission latency for the underwater acoustic channel. Section 2 explains the basic ideas and proposed schemes. In Sections 3 and 4, we mathematically analyze the performance of the proposed protocol. To confirm the mathematical analysis, we perform a simulation. The results of proposed protocol are compared with that of an existing S&W ARQ.

II. Proposed ARQ Scheme

2.1. Basic Ideas

We propose three basic ideas to overcome the effects of long propagation delay and a high BER.

First, we propose a concurrent bi-directional transmission to reduce the waste of time due to long propagation delay in the half-duplex acoustic modem. Under the condition of long propagation delay ($t_{prop} > 2\ t_{pkt}$), two nodes in communication can share a channel by the proper packet-scheduling without the packet collisions. Fig. 1 shows a possible scenario for concurrent bi-directional transmission. In the case of ($t_{prop} < 2\ t_{pkt}$), as shown in Fig. 1. (a), two nodes cannot avoid the collision. However, in the case of ($t_{prop} > 2\ t_{pkt}$), as shown in Fig. 1. (b), two node can share the channel if the packet is scheduled such a way that the events of packet transmission and reception do not occur at the same time at each node.

Second, we divide a packet into multiple sub-packets. By making the packet size smaller, the packet error probability can be reduced in an acoustic channel with high BER. Also, the smaller size of the sub-packet makes it easier to satisfy the condition of concurrent bi-directional transmission. The increased overhead caused by the sub-packet division is compensated by the improved performance and can be further reduced by selection of the optimal sub-packet size.

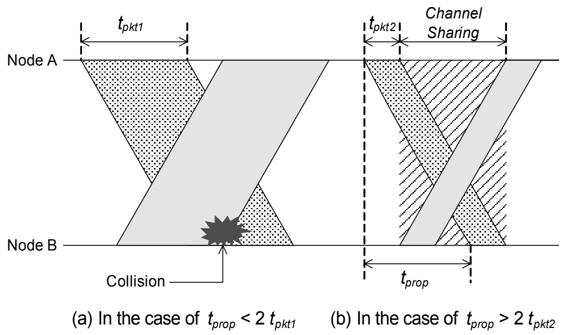

Fig. 1. Bi-directional transmission between two nodes.

Third, we replace a typical ACK signal by overhearing a backward data packet that is generated from the next intermediate node in the multi-hop networks. This overhearing reduces power consumption because an additional ACK signal does not need to inform the success. It also significantly reduces both ACK signal overhead and transmission latency.

2.2. Operation of the Proposed ARQ Scheme

Figure 2 shows a packet transmission flow through multiple nodes, where nodes A and D are source and destination, respectively. A data packet is divided into N fixed-size-sub-packets. The source node A sequentially transmits the sub-packets from 1 to N. Then, the relay nodes, B and C, immediately forward the received sub-packets to the next node if no error is found. This data relay causes a backward-overhearing to the previous nodes, as shown in Fig. 2. This backward-overhearing offers the recognition of successful transmission instead of the ACK signal. The destination node, D, needs to transmit a typical ACK signal.

In this concurrent bi-directional transmission scheme, the transmissions for all N sub-packets should be completed before the arrival of the

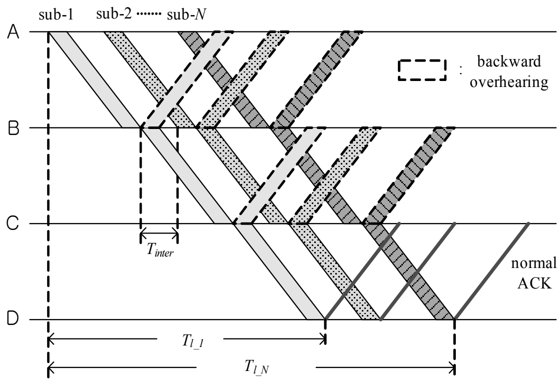

Fig. 2. Operation of the proposed ARQ scheme.

first sub−packet's acknowledgment (backward overhearing). That is,

$$2t_{prop} \geq (T_{inter} + t_{pkt})(N-1) + t_g \tag{1}$$

where, t_{prop} is the propagation delay of the hop, t_{pkt} is the duration of a data packet, and t_g is the guard time that considers propagation−delay variations of underwater channel. Also, T_{inter} is the interval between sub−packet trans−missions. T_{inter} should be controlled to avoid conflict with the backward overhearing and the sequential forward data transmission.

$$T_{inter} = 2(t_{pkt} + t_g) \tag{2}$$

If a node does not overhear the backward packet from receive−node within the transmission period, T, it should retransmit the original sub−packet. In the proposed scheme, the transmission period is defined as follows:

$$T = 2(t_{pkt} + t_{prop}) + t_{pkt} + t_g \tag{3}$$

where, additional t_{pkt} is included to prevent the collisions between a retransmitted sub−packet and a backward−overhearing sub−packet.

III. Mathematical Analysis

Latency is one of the important parameters used to measure the performance in ARQ schemes. In this paper, it is defined as the time taken to successfully transmit a data packet from the source node to the destination node.

We assume that a packet consists of an overhead and a payload. Thus, the data packet size is represented by:

$$B_p = b_{OH} + b_D \tag{4}$$

where b_{OH} is the number of overhead bits and b_D is the number of data bits. In the proposed ARQ scheme, the data packet is divided into N sub−packets. So, the payload size of the sub−packet is defined by the ratio b_D/N and there exists additional overhead bits. The sub−packet size is represented by:

$$B_{sub\_p} = b_{OH} + b_D/N \tag{5}$$

If p represents the bit error probability, then the sub−packet error probability is obtained by:

$$P_e = 1 - (1-p)^{B_{sub\_p}} \tag{6}$$

From Fig. 2, we define the dummy latency for sub−packet j, T_{l_j} as the elapsed time between the sub−packet 1's transmission at the source node and the sub−packet j's successful arrival at the destination node. For n hops and k retran−smissions, we can obtain T_{l_j} as follows:

$$T_{l\_j} = \sum_{i=1}^{n}(t_{pkt} + t_{prop}) + (j-1)(T_{inter} + t_{pkt}) + kT \tag{7}$$

Let P_{first_error} be the probability that the first error occurs at the i−th hop $(1 \leq i \leq n)$ in the n−hop system.

$$P_{first\_error}(i) = (1-P_e)^{i-1} P_e \tag{8}$$

Using (8), the probability that k errors occur in an n−hop system is represented by:

$$f(n,k) = \begin{cases} (1-P_e)^n & k = 0 \\ \sum_{i=1}^{n} P_{first\_error}(i) \times f(n+1-i, k-1) & k \geq 1 \end{cases} \tag{9}$$

The latency of proposed ARQ scheme is the maximum dummy latency of the sub-packets from 1 to N. That is,

$$T_L = max \lfloor T_{l\_j} \rfloor \quad , \; 1 \le j \le N \tag{10}$$

The cumulative distribution function (CDF) of T_L is

$$P(T_L \le y) = P(T_{l\_1} \le y,\, T_{l\_2} \le y,\, \cdots,\, T_{l\_N} \le y) \tag{11}$$

Because the dummy latency for each sub-packet is independent, (11) can be rewritten as follows:

$$P(T_L \le y) = P(T_{l\_1} \le y)P(T_{l\_2} \le y) \cdots P(T_{l\_N} \le y) \tag{12}$$

On the right-hand side of (12), the CDF for the dummy latency of each sub-packet can be obtained from (7) and (9). By applying them to (12), we can obtain the CDF for T_L. Finally, using the CDF for T_L, the average latency of the proposed ARQ scheme is represented by:

$$\overline{T_L} = \overline{T_L}(k=0) + \sum_{k=1}^{\infty}\left\{\sum_{j=1}^{N}\left\{T_{l\_j} \times (f(n,k)[h^{N-j}(k-1)]\,[h^{j-1}(k)])\right\}\right\} \tag{13}$$

where $h(k) = \sum_{m=0}^{k} f(n,m)$. And $\overline{T_L}(k=0)$ denotes the average latency when no packet error occurs.

$$\overline{T_L}(k=0) = \left[\sum_{i=1}^{n}(t_{pkt} + t_{prop}) + (N-1)(T_{inter} + t_{pkt})\right] f^N(n,0) \tag{14}$$

IV. Simulation & Results

In this section, the latency is numerically analyzed using a mathematical model and computer simulation. The system parameters for the simulation are summarized in Table 1. Here, we assumed t_g = 1/100 t_{prop}.

First, we derive the optimal sub-packet size to minimize the latency for the proposed ARQ scheme. Fig. 3 shows the latency for the proposed ARQ scheme versus number of sub-packets at $BER = 10^{-4}$. When the number of sub-packets is less than six; even though the burden time, such as T_{inter} and the overhead, increases with the number of sub-packets, the retransmission, due to packet error, is dominantly reduced by dividing a packet into multiple small sub-packets. Thus, the latency is improved as the number of sub-packets increases. In other part, when the number of sub-packets is larger than six; the latency increases with the number of sub-packets. This is because the increased burden time attenuates the effects of the reduced retransmissions due to smaller sub-packet. From Fig. 3, we can see that the optimum number of sub-packets is six, under the above conditions.

The optimum number of sub-packets depends on the system conditions, especially BER. In table 2, we derive the optimum number of sub-

Table 1. System parameter values.

Parameter	Value
Data rate	20 kbps
Data packet size	2000 bits
Overhead size	100 bits
BER range [9]	$10^{-6} \sim 10^{-3}$
Distance between nodes	500 m
Number of nodes	6
Speed of sound	1500 m/s

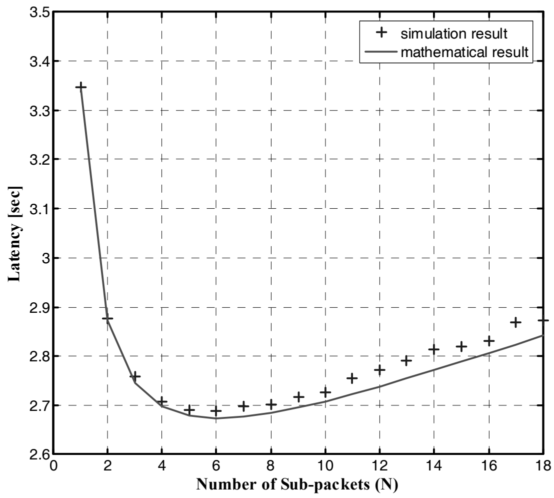

Fig. 3. The latency versus the number of sub-packets.

Table 2. The optimum number of sub-packets versus the bit-error rate.

BER	optimal N	BER	optimal N
$10^{-6} \sim 10^{-5}$	3	2×10^{-4}	8
$2\times10^{-5} \sim 5\times10^{-5}$	4	3×10^{-4}	11
$6\times10^{-5} \sim 7\times10^{-5}$	5	4×10^{-4}	13
$8\times10^{-5} \sim 10^{-4}$	6	$5\times10^{-4} \sim 10^{-3}$	18

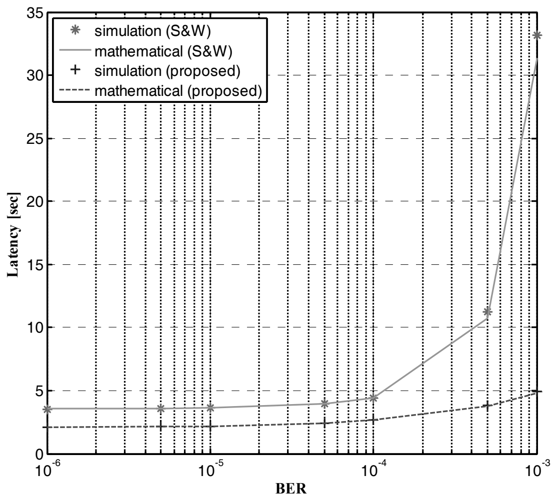

Fig. 4. The latency versus the bit-error rate.

packets on the various conditions of BER for the proposed ARQ scheme. Especially, under $BER=5\times10^{-4}$, a packet should be divided by $N=18$ to improve the latency.

In Fig. 4, we compare the proposed scheme with the S&W ARQ protocol by analyzing the latency for various BERs. In this simulation, the number of sub-packets for proposed scheme is optimized. The results show that the latency of the proposed scheme is much smaller than that of the S&W ARQ protocol, especially under a high bit error condition. In addition, the latency of the proposed scheme is better that of the S&W ARQ even when the channel condition is good. This is because the concurrent bi-directional transmission between a sender and a receiver and the backward overhearing instead of ACK signal reduce the waste of channel. On the bad channel conditions, such as underwater communication, the concept of multi sub-packets has a strong advantage.

V. Conclusions

In this paper, we proposed a latency-improved ARQ scheme for multi-hop UW-ASNs to overcome the characteristics of long propagation delay and a high BER. We introduced three concepts in the S&W ARQ protocol. These three concepts are the concurrent bi-directional transmission for the half-duplex acoustic modem, the multiple sub-packets for reduced retransmission at a high BER, and the overhearing backward data packets instead of a typical ACK signal for power and saving time. We mathematically analyzed the performance of this proposed scheme. To verify the mathematical analysis, we performed a computer simulation. The results showed that the latency for the proposed scheme is better than that of the S&W ARQ protocol in the underwater acoustic channel with long propagation delay and a high BER.

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