Performance Analysis of ARQ Protocols in Multiuser Underwater Acoustic Networks

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***Abstract*—The long propagation delay and the high bit error rate of underwater acoustic channel greatly affect the performance efficiency of underwater acoustic networks (UWANs). In this paper, we propose three ARQ schemes for UWANs, namely selective repeat-ARQ, Type-I Hybrid ARQ and Type-II Hybrid ARQ, where the transmissions of data and acknowledgment packets are interlaced. The proposed ARQ schemes are designed in the multiuser UWAN with single-hop network topology, and the media access control is the time division multiple access. The performance of the proposed ARQ schemes, in terms of the transmission efficiency and the average transmission delay of a packet, is analyzed, and the closed-form expressions of the performance metrics are derived. By comparisons, the best choices of the ARQ scheme in different network parameter scenarios are given.**

Keywords—Underwater acoustic networks; multiuser; reliable transmission; hybrid ARQ

I. INTRODUCTION

Underwater networks are attracting increasing significant interest with the need of ocean exploiting. Radio waves are extremely attenuated and light is strongly scattered and absorbed in underwater environment [1]. Hence, acoustic communication is the unique practical way for underwater networks.

There are specific characteristics for underwater acoustic networks (UWANs), such as the long propagation delay, the high bit error rate (BER), limited available bandwidth and the half duplex nature of most acoustic modems.

As we know, reliable data transmission is the prerequisite for designing efficient network protocols. However, the phase and amplitude fluctuations in UWANs lead to high BER. Hence, the error control techniques, the automatic repeat request (ARQ) schemes, and the forward error correction (FEC) schemes should be adopted to ensure the reliable data transmission in UWANs.

Moreover, the acoustic channel has strong attenuation with increasing frequency, which leads to very limited available bandwidth be shared by multiple users in the UWAN. Hence, appropriate medium access control (MAC) protocol should be design to coordinate and control the data transmissions in the sharing underwater acoustic channel.

The ARQ scheme is used to detect the transmission errors, and then to request the retransmission of erroneous packets. The most commonly employed policy is stop-and-wait ARQ (SW-ARQ) because of its simplicity and the half-duplex characteristic of underwater acoustic channel. However, the SW-ARQ has low throughput because the transmitter has to remain idle to wait the feedback from the receiver, and the long propagation delay is the characteristic of underwater acoustic channel.

To improve the throughput, several variants of classic SW-ARQ scheme have been proposed [2-4]. In [2], the basic SW-ARQ is improved so that data packets can be transmitted in a group and then be acknowledged selectively. In [3], a selective repeat ARQ mechanism is proposed, the typically long propagation delay of underwater acoustic channels is exploited in the scheme by interlacing the transmissions of data and acknowledgment (ACK) packets. Thus, the shortcoming of classic SW-ARQ, the transceivers remain idle during the whole round trip time (RTT), is prevented. In [4], two Hybrid ARQ (HARQ) schemes, namely Type-I HARQ and Type-II HARQ, are proposed for the UWANs. However, these proposed ARQ/HARQ schemes are discussed in the underwater acoustic channel scenarios, but not in multiuser UWAN scenarios. This is the motivation of our work.

In this paper, we focus on the error control mechanisms in multiuser UWANs. We propose three ARQ schemes in the multiuser UWAN environment, namely selective repeat-ARQ (SR-ARQ), type-I HARQ and type-II HARQ. In specific, the proposed ARQ schemes are designed in the multiuser UWAN with the single-hop network topology, and work well in combination with the time division multiple access (TDMA) protocol. The performance of the proposed ARQ schemes, in terms of the transmission efficiency and the average transmission delay of a packet, is analyzed, and the closed-expressions of the performance metrics are derived. The analytical results are validated by numerical simulations. By comparisons, the best choices of the ARQ scheme in different network scenarios are given.

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II. SYSTEM MODEL

A. System Model

We consider a multiuser UWAN as shown in Fig. 1, where the network topology is a centralized single-hop. The UWAN consists of one sink node and Q sensor nodes. The sensor nodes, a typical application of which is to function as the environmental monitoring in a given area, are anchored to the bottom of the ocean. The data collected by the sensor nodes are directly send to the sink node.

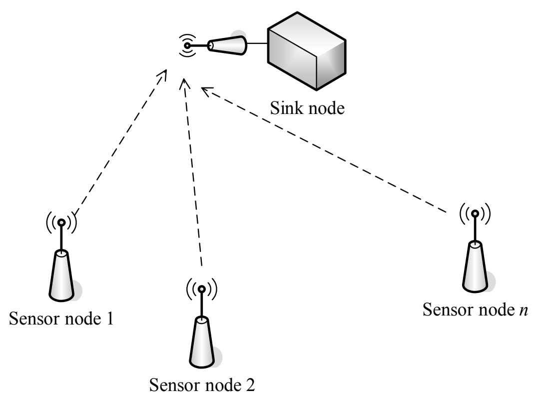

Fig. 1. The single-hop multiuser underwater acoustic networks.

Since the underwater acoustic channel is shared by multiple users in the UWAN, a MAC protocol to coordinate the usage of the shared media is necessary.

TDMA is a promising technique to handle the multiple access control problems caused by multiple sensors in UWAN, where networks are often small, and possible clock drift are negligible compared to the packet length due to low transmission rates. Assigning different time slots to sensor nodes can avoid data packet collisions and reduce energy consumption [5-8]. In this work, we assume that TDMA protocol is used to manage the data transmissions in the single-hop UWAN.

B. Determination of the System Parameters

It is assumed that plenty of data at the sensor nodes should to be sent to the sink node.

In the network set-up phase, the sink node sends hand-shaking packets to the sensor nodes in turn using a traditional stop-and-wait scheme. That is, the sink node first transmits a hand-shaking packet to one of the sensor nodes. Receiving the hand-shaking packets successfully, the sensor node returns an ACK to the sink node. Using the transmission of the hand-shaking packet and the receipt of its corresponding ACK, the sink node estimates the RTT between itself and the sensor node. If the sink node does not receive ACK from a sensor node, it repeats the hand-shaking process until a given maximum retransmission times, N_T, achieves.

Let RTT_i denote the RTT between the sink node and the sensor node i. The time slot of the TDMA protocol is set as

$$T_{\text{slot}} = n \times \max_{i \in \{1,2,\ldots,Q\}} \{RTT_i\} . \quad (1)$$

In (1), the maximum of all RTTs is chosen to ensure that all the sensor nodes in the UWAN can transmit at least one packet in a time slot.

For the sensor node i, the length of transmission window, M_i, is defined as the maximum number of data packets that can be transmitted before waiting for ACK. Hence, M_i is

$$M_i = \max\left(1, \left\lfloor \frac{2d_i/c}{T_{\text{DATA},i} + T_{\text{Guard},i} + T_{\text{ACK},i}} \right\rfloor\right), \quad (2)$$

where d_i is the distance between the sink node and sensor node i. c is the sound speed. $T_{\text{DATA},i}$ and $T_{\text{ACK},i}$ are the transmission time of data packet and ACK packet, respectively. $T_{\text{Guard},i}$ is the guard time of time slot.

The number of data packets, that a sensor node can be sent in a time slot, is

$$N_i = \left(\left\lfloor \frac{T_{\text{slot}}}{RTT_i} \right\rfloor - 1\right) \times M_i + 1 . \quad (3)$$

The data packets to be sent in the current time slot should include the data packets that transmitted failed in the previous time slots. Hence, the structure of data packets at sensor node i in the tth time slot is given in Table 1.

The number of the jth retransmission data packets is $K_t(j) = N_i P_{c,i}(j)$, and the number of the original data packets is $K_t(0) = N_i - N_i \sum_{j=0}^{N_T} P_{c,i}(j)$, where $P_{c,i}(k)$ is the probability of a data packet received correctly from sensor node i until the kth retransmission.

III. PERFORMANCE ANALYSIS

After the network is setup, the data collected by sensor nodes should be sent to the sink node. The error control schemes, the SR-ARQ, type-I HARQ and type-II HARQ, are used in case of error occurrence during the transmission. In this section, we will derive the numerical performance analysis of different error control schemes in UWANs.

A. The SR-ARQ Scheme

The SR-ARQ scheme employs a form of time division duplex (TDD). The idea behind SR is that the typically long propagation delay of underwater acoustic channels can be exploited to pack several data packet transmissions within the same RTT, while keeping the receiver silent when it is expected to receive ACKs [9].

The flow of the transmission where three data packets are transmitted before listening the ACKs is illustrated in Fig. 2. The knowledge of the RTT, an essential condition for the SR-ARQ scheme, can be obtained by measuring the timing of the data/ACK exchange by performing a preliminary stop-and-wait hand-shaking scheme in subsection II-B.

TABLE I. THE PACKET STRUCTURE OF THE TTH TIME SLOT FOR ITH NODE

N_Tth retransmission packets	(N_T-1)th retransmission packets	…	1st retransmission data packets	Original data packets
$K_t(N_T)$	$K_t(N_T\text{-}1)$		$K_t(1)$	$K_t(0)$

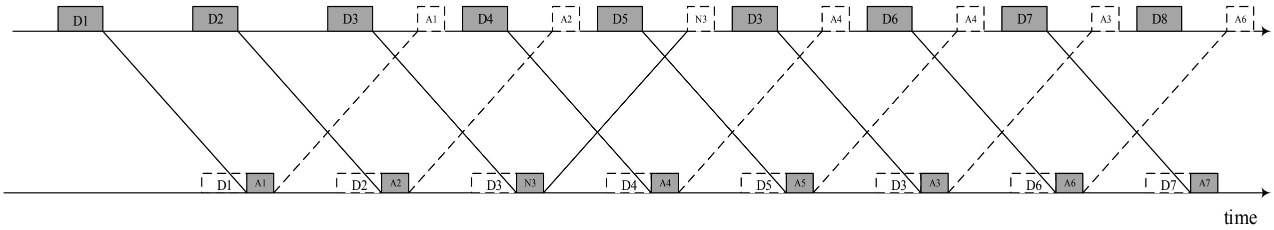

Fig. 2. The flow of the selective repeat transmission technique

The probability of transmitting a data packet correctly without no retransmissions is $P_{c,i}(0) = (1 - P_{\mathbf{b},i})^L$, where $P_{b,i}$ is the BER of the channel between the sink node and the ith sensor node, and L is the length of the data packet.

For the SR-ARQ scheme in the UWAN, the probability of transmitting a data packet successfully until the kth retransmission is

$$P_{c,i}(k) = (1 - P_{c,i}(0))^k P_{c,i}(0) \ . \tag{4}$$

For the SR-ARQ scheme in the UWAN, the valid number of data packets transmitted successfully in a time slot for sensor node i is

$$D_{\mathbf{VALID},i} = N_i P_{c,i}(0) \, . \tag{5}$$

For the SR-ARQ scheme in the UWAN, the average delay of transmitting a packet successfully in a time slot for sensor node i is

$$\overline{T}_{\mathbf{SR\text{-}ARQ},i} = \frac{T_{\mathbf{SLOT}}}{D_{\mathbf{VALID},i}} = \frac{T_{\mathbf{SLOT}}}{N_i P_{c,i}(0)} \ . \tag{6}$$

The average delay of transmitting a packet successfully in a time slot of the SR-ARQ scheme for the UWAN is

$$\overline{T}_{\mathbf{SR\text{-}ARQ}} = \frac{1}{Q} \sum_{i=1}^{Q} \overline{T}_{\mathbf{SR\text{-}ARQ},i} \ . \tag{7}$$

The network throughput of the SR-ARQ scheme for the UWAN is

$$\eta_{\mathbf{SR\text{-}ARQ}} = \frac{\sum_{k=1}^{Q} D_{\mathbf{VALID},k}}{\sum_{k=1}^{Q} N_k} = \frac{\sum_{k=1}^{Q} N_k P_{c,k}(0)}{\sum_{k=1}^{Q} N_k} \ . \tag{8}$$

B. Type-I HARQ Scheme

Due to the high BER in the underwater acoustic channel, the retransmission of data packets is always frequent, and the transmission of the retransmitted packets may be erroneous using the basic ARQ schemes. Hence, the HARQ schemes with the capability of correcting possible erroneous bits in data packets should be introduced to reduce some unnecessary retransmissions. In this work, we consider two commonly used HARQ schemes, namely type-I HARQ and type-II HARQ [4].

For the type-I HARQ, the transmitter encodes the information bits by FEC with correction capability t. If the received data packets are error-free or the number of erroneous bits of the received data packet is within the correction capability, the receiver accepts the data packets and sends an ACK to the transmitter. After that, the transmitter sends new data packets when ACKs are received, or retransmits the failure data packets.

The probability of transmitting a data packet correctly without retransmission is $P_{c,i}(0) = \sum_{k=0}^{t} \binom{H+L}{k} (1 - P_{\mathbf{b},i})^{H+L-k} P_{\mathbf{b},i}{}^k$, where L is the length of the data packet and H is the length of a packet header.

For type-I HARQ scheme in the UWAN, the probability of transmitting a data packet successfully until the kth retransmission is

$$P_{c,i}(k) = (1 - P_{c,i}(0))^k P_{c,i}(0) \ . \tag{9}$$

For type-I HARQ scheme in the UWAN, the valid number of data packets transmitted successfully in a time slot for sensor node i is

$$D_{\mathbf{VALID},i} = N_i P_{c,i}(0) \frac{L}{H+L} \ . \tag{10}$$

For type-I HARQ scheme in the UWAN, the average delay of transmitting a packet successfully in a time slot for sensor node i is

$$\overline{T}_{\mathbf{HARQ\text{-}I},i} = \frac{T_{\mathbf{SLOT}}}{N_i P_{c,i}(0)} \left(1 + \frac{H}{L}\right). \tag{11}$$

The average delay of transmitting a packet successfully in a time slot of the type-I HARQ scheme for the UWAN is

$$\overline{T}_{\mathbf{HARQ\text{-}I}} = \frac{1}{Q} \sum_{i=1}^{Q} \overline{T}_{\mathbf{HARQ\text{-}I},i} . \tag{12}$$

The network throughput of the type-I HARQ scheme for the UWAN is

$$\eta_{\mathbf{HARQ\text{-}I}} = \frac{L}{H+L} \frac{\sum_{k=1}^{Q} N_k P_{c,k}(0)}{\sum_{k=1}^{Q} N_k} . \tag{13}$$

C. Type-II HARQ Scheme

For Type-II HARQ scheme, the transmitter sends a data packet to the receiver, and at the same time, the transmitter will calculate the parity packet which could recover the data packet by means of decoding.

In case of error occurrence in the previous transmitted data packet, the receiver will store the erroneous data packet into the buffer for later correction. The transmitter will send the parity packet instead of the data packet. If the retransmitted parity packet also has erroneous bits, it will be combined with the error data packet stored in the buffer, and then be processed by the error correction. If the error correction fails, the parity packet is stored in the buffer, and the failed data packet will be retransmitted. In this way, data packets and parity packets are retransmitted in turn.

The probability of transmitting a data packet correctly without retransmission is $P_{\mathbf{c},i}(0) = P_{\mathbf{err}}(0)$, where $P_{\mathbf{err}}(k)$ denotes the probability that there are k error bits out of (H+L) bits in the received packet, and $P_{\mathbf{err}}(k) = \binom{H+L}{k} (1 - P_{\mathbf{b},i})^{H+L-k} P_{\mathbf{b},i}{}^{k}$.

For the type-II HARQ scheme in the UWAN, the probability of transmitting a data packet successfully until the kth retransmission for sensor node i is

$$\begin{aligned} P_{\mathbf{c},i}(k) = & \underbrace{\sum_{j_k=1}^{t-j_{k-1}} P_{\mathbf{err}}(j_k) \sum_{j_{k-1}=t-j_{k-2}+1}^{t-1} P_{\mathbf{err}}(j_{k-1}) \ldots \sum_{j_1=t-j_0+1}^{H+L} P_{\mathbf{err}}(j_1) \sum_{j_0=1}^{H+L} P_{\mathbf{err}}(j_0)}_{k+1} \\ & + P_{\mathbf{err}}(0) \underbrace{\sum_{j_{k-1}=t-j_{k-2}+1}^{H+L} P_{\mathbf{err}}(j_{k-1}) \ldots \sum_{j_1=t-j_0+1}^{H+L} P_{\mathbf{err}}(j_1) \sum_{j_0=1}^{H+L} P_{\mathbf{err}}(j_0)}_{k} \end{aligned} . \tag{14}$$

For the type-II HARQ scheme in the UWAN, the valid number of data packets transmitted successfully in a time slot for sensor node i is

$$D_{\mathbf{VALID},i} = N_i P_{c,i}(0) \frac{L}{H+L} . \tag{15}$$

For the type-II HARQ scheme in the UWAN, the average delay of transmitting a packet successfully in a time slot for sensor node i is

$$\overline{T}_{\mathbf{HARQ\text{-}II},i} = \frac{T_{\mathbf{SLOT}}}{N_i P_{c,i}(0)} \left(1 + \frac{H}{L}\right). \tag{17}$$

The average delay of transmitting a packet successfully in a time slot of the type-II HARQ scheme for the UWAN is

$$\overline{T}_{\mathbf{HARQ\text{-}II}} = \frac{1}{Q} \sum_{i=1}^{Q} \overline{T}_{\mathbf{HARQ\text{-}II},i} . \tag{18}$$

The network throughput of the type-II HARQ scheme for the UWAN is

$$\eta_{\mathbf{HARQ\text{-}II}} = \frac{L}{H+L} \frac{\sum_{k=1}^{Q} N_k \cdot P_{c,k}(0)}{\sum_{k=1}^{Q} N_k} . \tag{19}$$

D. Calculation of Parameters

In the actual network, there are always some rules for these proposed ARQ schemes to ensure the operation of the network.

Assume that the BER is required to be less than P_i, and the average delay of transmitting a packet successfully is required to be less than T_i. Hence, we obtain

$$P_e = 1 - \sum_{i=0}^{N_T} P_c(i) < P_i , \tag{20}$$

and

$$\overline{T}_{x,i} = \frac{T_{\mathbf{SLOT}}}{N_i P_{c,i}(0)} < T_i , \tag{21}$$

where the subscript x in $\overline{T}_{x,i}$ means SR-ARQ, type-I HARQ or type-II HARQ.

From (21), we obtain $P_{c,i}(0) > \frac{T_{\mathbf{SLOT}}}{N_i \cdot T_i}$. Hence, we can obtain suitable value of the length of a packet header, H, and the length of the data packet, L, with the knowledge of the BER in the network.

After that, we can get the maximum retransmission times, N_T.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of three ARQ schemes in a UWAN, in terms of the average delay of a packet and the throughput efficiency.

The simulation parameters are set as Q=5, N_T=3, d=10 km, r=2 kbps, c=1500 m/s. For SR-ARQ scheme, L=1023 bits. For HARQ schemes, H=16 bits, L=1007 bits [4].

A. Network throughput

Fig. 3 shows the network throughput of three ARQ schemes in the UWAN. From Fig. 3, we observe that the throughput of three ARQ schemes is high and approaches to 1 when the BER is low enough. And as the BER increase, the throughput of three ARQ schemes decreases.

However, the impact of the BER on the network throughput of three ARQ schemes is different. When the BER is lower than 0.001, the network throughput of the type-I HARQ scheme is the highest among three ARQ scheme, and decreases little because the possible error bits in the data packets is within the correction capability, and no retransmissions are needed. And for the type-II HARQ scheme, the network throughput is higher than the SR-ARQ scheme but lower than the type-I HARQ scheme. Moreover, the impact of the BER on the network throughput of the type-II HARQ scheme is less than that of the SR-ARQ scheme. The reason for this phenomenon is that the retransmitted parity packet and its original data packet can be combined to correct errors to reduce some possible retransmissions.

When the BER is higher than 0.001, the network throughput of the type-I HARQ scheme decreases rapidly because the erroneous bits in data packets overrun the correction capability. And we can get the same phenomenon in the type-II HARQ scheme with t=10 when the BER is higher than 0.002, and the type-II HARQ scheme with t=20 when the BER is higher than 0.005. When the BER is much large, the HARQ schemes with higher correction capability have higher network throughput than those with a lower correction capability and without correction capability.

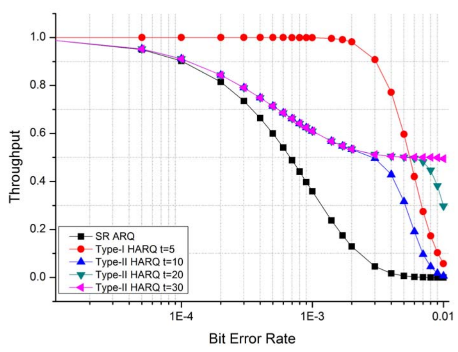

Fig. 3. The network throughput of three ARQ schemes in the UWAN.

B. Average transmission delay

Fig. 4 shows the average transmission delay of three ARQ schemes in the UWAN. For comparison, we also give the the average transmission delay of traditional SW ARQ scheme in the UWAN.

From Fig. 4, we observe that the performance of traditional SW ARQ scheme in terms of the average transmission delay performs much less than three proposed ARQ schemes. The reason for this phenomenon is that the transceivers remain idle during the long propagation delay in the SW ARQ scheme. And the proposed ARQ schemes reduce the average packet transmission delay by transmitting data packets or receiving ACKs during the long propagation delay.

When the BER is sufficient low, the performance of the SR-ARQ and HARQ schemes in terms of the average transmission delay perform almost the same. This is because there are few errors in the transmitted data packets and no retransmissions are needed.

As the BER becomes larger, the average transmission delay of the type-I HARQ scheme remains because of its correction capability avoids some retransmissions. However, the average transmission delay of the type-II HARQ scheme and the SR-ARQ scheme increases. And the average transmission delay of the SR-ARQ scheme increases more rapidly than that of the type-II HARQ scheme. This is because the error bits in data packets occur, and retransmissions are needed, but the correction capability of the type-II HARQ scheme reduces the number of retransmission.

When the BER becomes quite large, the average transmission delay of the type-II HARQ scheme with t=30 performs the best. The reason for this phenomenon is that the number of the error bits in packets is still within its correction capability.

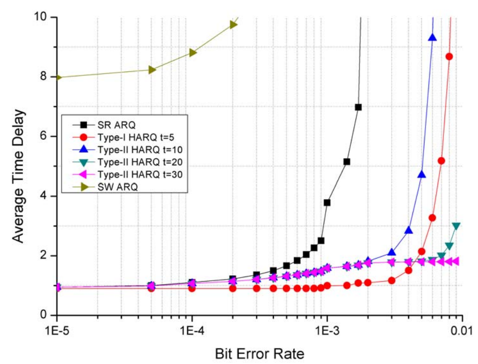

Fig. 4. The average transmission delay of different ARQ schemes in the UWAN.

V. CONCLUSIOINS

In this paper, we proposed the reliable transmission scheme in the multiuser UWANs, in which the SR technique is combined with the ARQ schemes and the long propagation delay is exploited by interlacing the transmission of the data packet and ACK. Moreover, we also designed the ARQ schemes considering the characteristics of the MAC protocol in the multiuser UWAN. The TDMA protocol is considered in this work. The performance of three ARQ schemes in the

UWAN, namely the SR-ARQ, the type-I HARQ and the type-II HARQ, are analyzed, and the closed-expressions are derived. The analytical results are verified by simulations. The simulation results show that the technique of interlacing the transmission of data and ACK packets improves the performance of the traditional SW ARQ scheme obviously. And the HARQ schemes perform better than the SR-ARQ scheme, in terms of a higher network throughput and a lower average packet transmission delay. When the BER is lower than 0.005, the performance of the type-I HARQ scheme is the best among three ARQ schemes. When the BER is high, the correction capability affects the performance obviously.

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