ADAPTIVE RTT-DRIVEN TRANSPORT-LAYER FLOW AND ERROR CONTROL PROTOCOL FOR QoS GUARANTEED IMAGE TRANSMISSION OVER MULTI-HOP UNDERWATER WIRELESS NETWORKS: DESIGN, IMPLEMENTATION, AND ANALYSIS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2013

Major Subject: Computer Engineering

ABSTRACT

With the rapid advances in data transmission over various advanced underwater acoustic networks, it is important to develop the efficient protocol to obtain a high data-rate with Quality of Service (QoS) guarantee requirements for acoustic wireless communications. Because of the harsh underwater acoustic environments, such as time-varying network topology and channel conditions, limited bandwidth and constrained underwater signal propagation, we develop and implement a protocol called multi-hop adaptive RTT-driven transport layer flow and error control protocol (ARTFEC) for QoS guaranteed image transmission in underwater wireless networks. ARTFEC is based on the congestion window size control and the Q-learning optimal timeout selection with QoS provisioning. For the congestion window size control, we propose an RTT-based data flow control policy to adapt to the varying acoustic channel environments, aiming to guarantee the reliability and high data rate of data transmission. In addition, we develop a Q-learning based optimal timeout selection algorithm to improve the channel utilization efficiency, which can increase the end-to-end throughput while decreasing the packet loss rate. We implement ARTFEC using our lab testbed, which consists of the Aqua-Net protocol stack and the acoustic OFDM modems. The testbed results obtained show that our developed ARTFEC transport layer protocol outperforms the other existing reliable data transmission schemes, in terms of end-to-end throughput and packet loss rate.

DEDICATION

To my parents and grandparents.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my advisor, Professor Xi Zhang, who gives me constant guidance as well as warm encouragement throughout this research project. He is always patient, kind, and helpful whenever I have questions about my academic life. I cannot complete this thesis without his guidance and generous support. I also would like to thank Professor Erchin Serpedin and Professor Anxiao Jiang for being my committee members, and for their suggestions on this thesis.

Last but not least, thanks to my lab mate Ping Wang in the Networking and Information Systems Laboratory and all my friends and colleagues who helped me during all these years and also the department faculty and staff for providing me a warm and kind environment during my studies at Texas A&M University.

NOMENCLATURE

QoS	Quality of Service
ARTFEC	Adaptive RTT-Driven Transport-Layer Flaw and Error Control
OFDM	Orthogonal Frequency Division Multiplexing
TCP	Transport Control Protocol
RTT	Round-Trip-Time
MAC	Media Access Control

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

With the rapid developments in technology, underwater acoustic communication has become an important data transmission technology [1][2], which is widely applied in commercial and military ocean technology, including oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance [3]. In underwater acoustic wireless network, several implementation challenges such as including low communication bandwidth, large propagation delay, half-duplex modem working mechanism, long hardware processing time, and high bit-error rate need to be considered to maintain a high performance in such highly unstable and indistinct environment. Since underwater acoustic communications is much more challenging than onshore radio communications [4], even radio signals are not suitable to be transmitted in underwater wireless networks due to the severe attenuation in underwater environment. However, acoustic signals can be efficiently transmitted through the underwater wireless channels, as shown in Fig. 1, so hydrophones are widely used for sending and receiving message. Therefore, developing acoustic communication protocol is very important for implementing the high-data-rate, highly reliable, and multi-transmit modes communications with limited bandwidth over underwater wireless networks.

Underwater acoustic network protocol stack, as shown in Fig. 2, is very similar to Open Systems Interconnection (OSI) model, which has several protocol layers with different functionalities as follows:

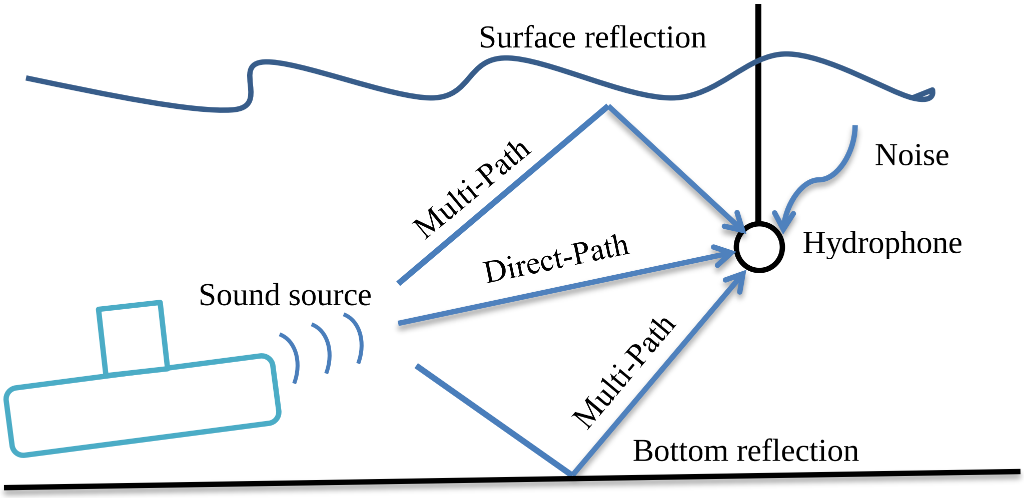

Figure 1. Underwater Acoustic Wireless Network.

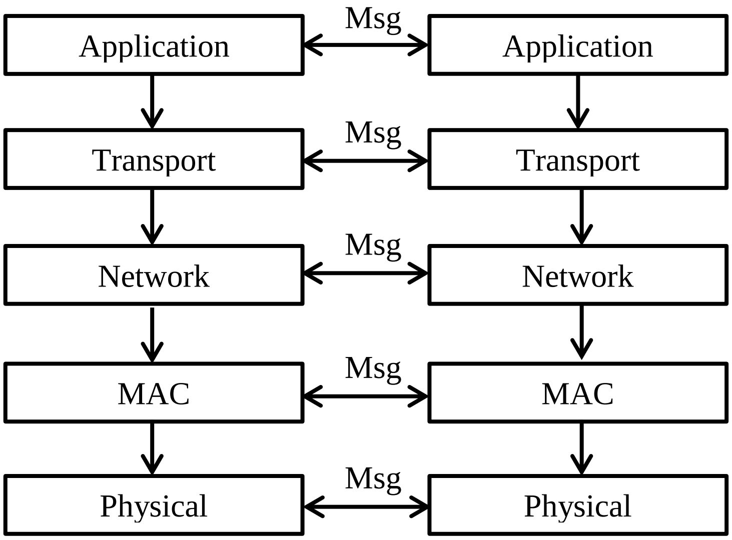

Figure 2. Underwater Acoustic Network Stack.

Physical Layer: The physical layer combines the basic data transmission hardware configurations and responsible for physically sending and receiving data packets of the acoustic network.

MAC Layer: The MAC layer provides the addressing mechanism and channel (media) access control mechanism.

Network Layer: The network layer gives routing methods, host addressing and message forwarding functions.

Transport Layer: The transport layer provides the end-to-end communication services for applications, the QoS provision and reliability of the data transmission are guaranteed and designed in transport layer, and it also provides flow control and congestion control mechanism.

Application Layer: The application layer works as user interface, it provides the service as read image and writes the received packet to set up the whole file.

To overcome the challenges in underwater acoustic data transmission, and to achieve a reliable image transmission, it is important to develop a reliable transport layer protocol with reliability and flow control and congestion avoidance mechanism, which should be able to adapt to the change of underwater environment rapidly. Besides, increasing the transmission throughput is another important goal when designing the transport layer protocol, which can be achieved by several mechanisms, include avoidance of redundant retransmission and reduce of redundant ACK. Since the severe signal attenuation in acoustic channels and the long distance application in underwater environment, the single-hop underwater wireless communication is impossible. Thus, the hop-by-hop scheme is necessary for underwater wireless networks. In recent years, a couple of schemes dedicated to underwater acoustic network data transmission have been proposed to implement reliable high data transmission such as Stop-and-Wait automatic repeat request technique (ARQ), Segmented Data Reliable Transfer (SDRT) [5], and Aqua-SARQ (a TCP-like end-to-end scheme based on a sliding window and selective repeat) scheme. We have implemented those protocols in our lab testbed to evaluate their performances. From the results, we observed that some issues need to be resolved.

For Stop-and-Wait ARQ, although it can ensure that the data packet is not lost due to dropped packets and all the packets are received in a correct order, there has a significant end-to-end delay due to the multiple retransmissions if in case of packet loss and high error probabilities over underwater acoustic communication networks, and the transmission speed are limited due to the fixed sliding window size. In Aqua-SARQ scheme, although it has sliding window control and the selective repeat mechanism, it did not take the time-varying features of underwater network into account. Thus, the approach cannot adapt to the various acoustic environment timely. The authors in [5] proposed a hybrid protocol including a coding scheme with ARQ and a novel window control mechanism, which greatly improve the system's energy efficiency and channel utilization. However, they didn't consider the time-varying acoustic channel characteristic and the QoS provisioning [6], [7] for data transmission either. Besides, Transmission Control Protocol (TCP) is widely used in wire-based communication, and although TCP has a time-out control scheme and adaptive window size control mechanism, it lacks sensitivity and flexibility to detect the changes in the environments.

To address above problems, as well as maintain the reliability and high-throughput performance, we propose and develop an adaptive RTT-driven transport-layer flow and error (ARTFEC) control protocol for QoS guaranteed image transmission over multi-hop underwater wireless networks. This protocol is a combination of adaptive congestion window (ACWND) control scheme and Q-learning timeout selection mechanism with QoS provisioning. The novel ACWND is proposed to adapt to the varying acoustic channel environment, aiming to guarantee the reliability and high data rate of image transmission.

Since the underwater acoustic channel is time-varying, the RTT is always changing. After packets transmission, if the sender receives an ACK, it implies that the transmission is successful. Otherwise, the sender has to retransmit the same packets one more time. The sender will decide whether to retransmit packets within the duration of timeout. Thus, the value of timeout needs to be carefully assigned to avoid unnecessary retransmissions or to shorten the waiting time for ACK.

Fig. 3 and Fig. 4 show two problematic situations when the timeout value is not set properly. Fig. 3 illustrates the scenario when timeout value is short. In this case, the receiver successfully receives all packets while the sender receives an ACK later than the timeout. Thus, the retransmission of packet 1 is unnecessary. Fig. 4 shows the scenario when no ACK is received at the sender side. In this case, the sender will retransmit after timeout. If the timeout is too long, the channel will become idle which thus decreases the channel utilization.

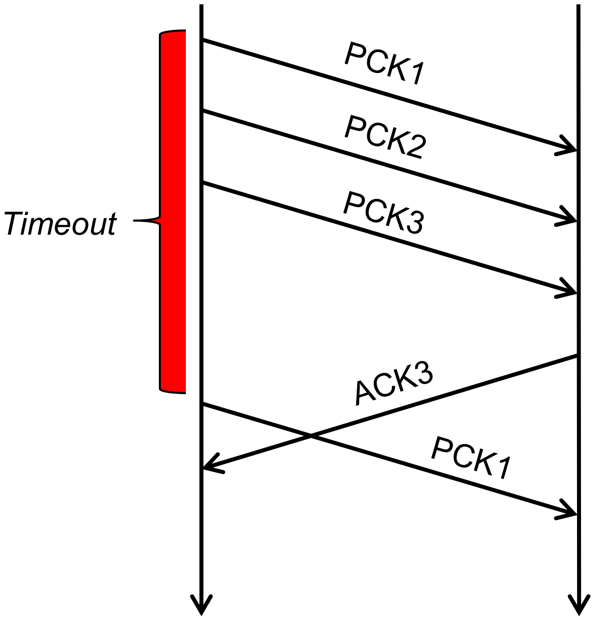

Figure 3. Inappropriate timeout setting (Short).

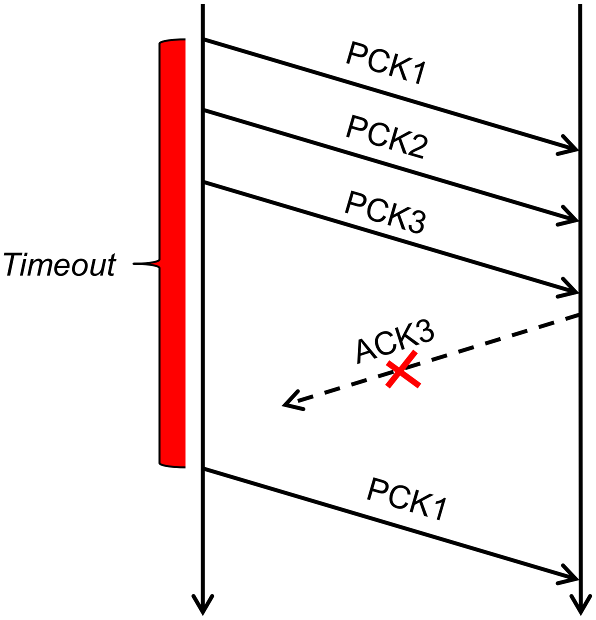

Figure 4. Inappropriate timeout setting (Long).

In addition, Q-learning [8] based optimal timeout selection algorithm is developed to solve above problems to improve the channel efficiency, which is a model-free reinforcement learning technique, and can be used to find an optimal action-select policy for any given Markov decision process (MDP). It works by learning an action-value function which gives the expected utility of taking a given action in a given state, when following the optimal policy thereafter. When such an action-value function is learned, the optimal policy can be constructed by simply selecting the action with the highest value in each state. In our work, Q-learning algorithm is used to make the decision on timeout selection, which can make a great improvement on channel utilization. ARTFEC is designed to achieve the goals of reliable high data rate transmission with QoS guaranteed over multi-hop underwater wireless acoustic networks. We have implemented ARTFEC on a lab testbed [9], which consists of a water tank, a set of communication hardware and software application programming interfaces (APIs), to evaluate its performance.

The thesis is organized as follows. Chapter 2 presents the design of ARTFEC, describing the adaptive congestion window control and the Q-learning timeout selection algorithm. Chapter 3 demonstrates the implementation details of ARTFEC. Chapter 4 evaluates the proposed protocol and gives the initial lab test results. The thesis concludes with Chapter 5.

2. PROTOCOL DESCRIPTION

ARTFEC, as shown in Fig. 5, is a combination of an adaptive congestion window (ACWND) control scheme and a Q-learning timeout selection mechanism. ACWND, which is a delay-based data flow control policy, is proposed to adapt to the time-varying acoustic channel environment, and aims to guarantee the reliability and high data rate of data transmission. Q-learning is a reinforcement learning technique that solves decision problems. By analyzing the underwater environment and evaluating an action-value function, Q-learning gives the expected reward of taking an action in a given state, according to which the distributed learning agent is able to make a decision automatically. ARTFEC is designed to achieve the goal of reliable high data rate transmission with QoS guaranteed in underwater acoustic wireless networks. We next describe how these two parts are used in the proposed protocol.

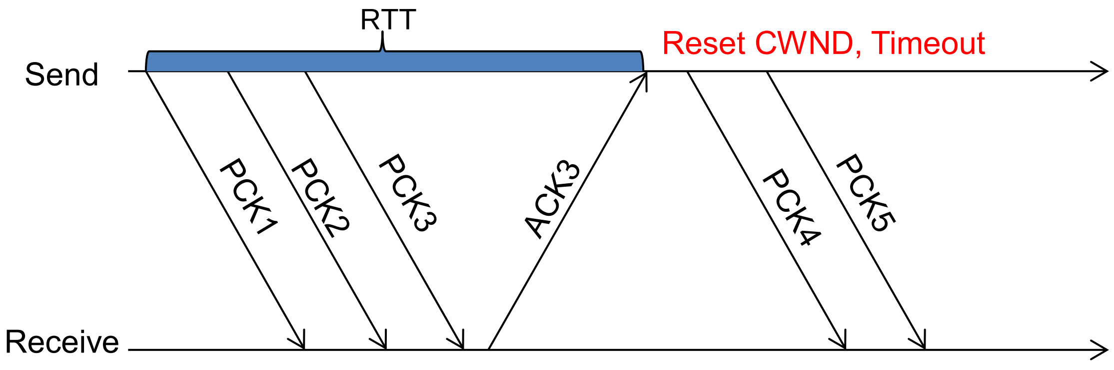

Figure 5. ARTFEC Protocol Overview.

2.1 Adaptive Congestion Window Control

Because of the time-varying underwater environment, the status of the acoustic channel is not stable. For the purpose of achieving a reliable high data rate transmission, using the multiple window flow policy is required. In this thesis, we propose an adaptive congestion window control scheme based on the RTT, as shown in Fig. 6, which is the total delay needed for the data packet transmission between the source node and the destination node, and can be obtained by:

$$\text{RTT} = T_{tran} + T_{pro} + T_{sys} + T_{ACK} + T_{wait} \tag{1}$$

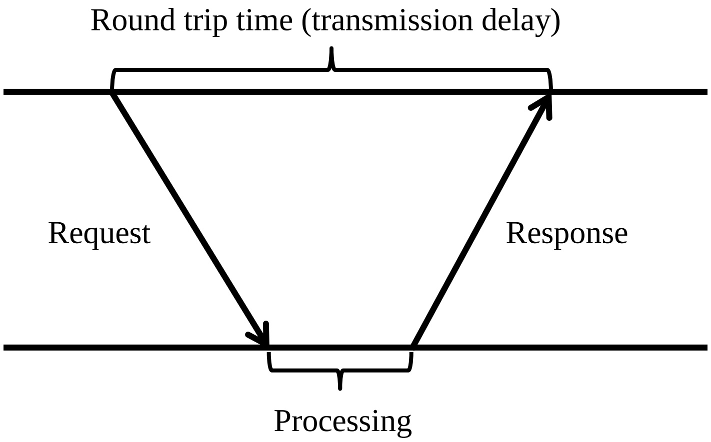

Figure 6. Round-Trip-Time (RTT).

where T_{trans} is the data packet transmission delay and $T_{trans} = L_p/R$, where L_p is the packet size including overheads in bits, and R is the acoustic modem rate, determined by the modem hardware. T_{pro} is the propagation delay and $T_{pro} = L_p/C$, where C is the acoustic speed (1500m/s). T_{sys} is the acoustic network system processing delay including signal enhancement, frame format, and synchronization. T_{ack} is the ACK packet transmission delay, T_{wait} is the timeout delay for avoiding the channel congestion between the packet sending and receiving.

Due to the time-varying underwater acoustic channel, the instantaneous RTT is a variable. In order to maximize the network throughput, we propose an adaptive congestion window control scheme based on the RTT in each epoch. We decide the status of the acoustic network through the RTT feedback information, which is obtained by the time clock in data and ACK packet transmission. At first, we denote the weighted average throughput of network congestions by V_n, where n is the number of network congestion durations, derived by

$$V_n = \sum_{i=1}^{n} V_i \frac{w_n(i)}{\sum_{i=1}^{n} w_n(i)} \tag{2}$$

where V_i is the throughput of the i_{th} congestion throughput, and $W_n(i)$ is the weighted coefficient of the i_{th} congestion duration, calculated by

$$w_n(i) = \begin{cases} 1 & \left(1 \leq i \leq \frac{n}{2} \right) \\ \frac{n+1-i}{\frac{n}{2}+1} & \left(\frac{n}{2} \leq i \leq n \right) \end{cases} \tag{3}$$

Thus, by comparing between V_n and the instantaneous throughput $V(t)$ at epoch t, we can obtain the channel status of current acoustic networks, and then adjust the congestion window adaptively, which is derived by

$$cwnd(t+1) = \begin{cases} cwnd(t) + 1 & V(t) > 2V_n \\ cwnd(t) + \alpha & 2V_n > V(t) > V_n \\ cwnd(t) \cdot \beta \cdot \frac{V(t)}{V_n} & V_n > V(t) > V_n/2 \end{cases} \tag{4}$$

where *cwnd(t)* denotes the current congestion window size, *cwnd(t+1)* denotes the congestion window size at next epoch, α and β are two adjustable parameters ($0<\alpha<1$, $\beta>0$), and V(t) is denoted by

$$V(t) = \frac{l_p}{RTT(t)} \tag{5}$$

where *T(t)* denotes the instantaneous RTT at epoch *t*.

By the following example, we explain these equations intuitively, Assuming current congestion window size is 5, and thus, we send these 5 data packets simultaneously. There are four possible situations during image transmissions, as shown in Fig. 7, which are described as follows:

1). ACK 5 feedback: The receiver R gets all the 5 packets successfully, and then sends an ACK 5 back to the sender S. In this case, V_n is not necessarily updated since no congestion has happened. Therefore, we only need to calculate the new window size through Eq. (4);

2). NACK 3 feedback: The receiver *R* detects an error packet (the packet 3 as shown in Fig 1). Then, the receiver sends an NACK 3 to notice the sender *S* that packet 3 should be retransmitted, but no need to update V_n;

3). No ACK feedback: The sender *S* does not receive any ACK, then it will retransmit these 5 packets one by one until get an ACK from *R*. In this case, we need to update V_n because of the network congestion, and also calculate the new congestion window size.

4). ACK 2 feedback: The receiver *R* send an ACK 2 to notice the sender *S* that packet 3 was dropped. Then, *S* will not retransmit packet 3 until the timeout, by which the unnecessary retransmit can be avoided, thus improving the channel utilization

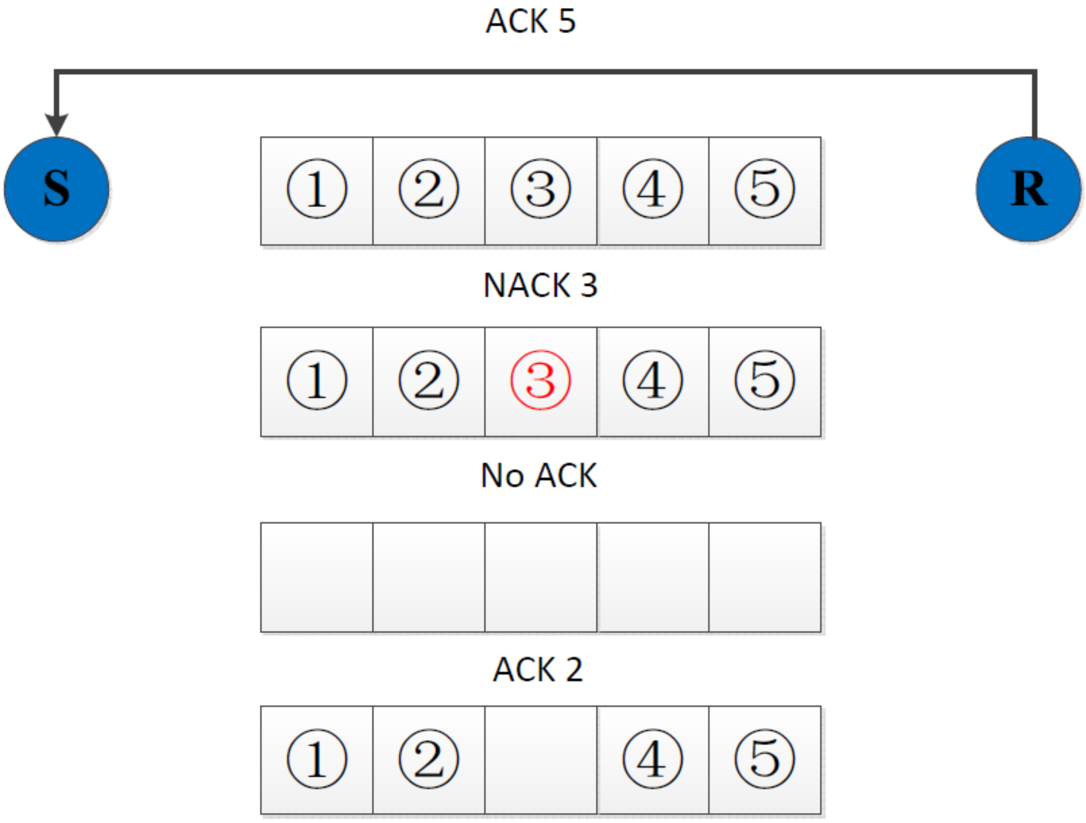

Figure 7. Four situations of multiple congestion windows for single-hop image transmissions between the sender S and the receiver R.

The pseudocode of the adaptive RTT-driven congestion window (ARCW) control algorithm is listed in Algorithm 1 as follows:

Algorithm 1 The ARCW control algorithm

```
1) Initialization;
```

```
2) Initialize the average congestion throughput $V_n$;
3) Select a current congestion window size N;
4) Transmit the multiple N packets;
5) If ACK number < N;
6) If wait time > timeout
        Retransmit the packet (number+1), update $V_n$ through
        Eq. (2) and calculate the new CWND size through
        Eq. (4);
7) Else If wait time < timeout
        Wait for ACK until reach the timeout, then return to 7);
8) End if.
9) Else If Feedback is NACK
        Retransmit the NACK number packet, calculate the new
        CWND size through Eq. (4);
10) Else If ACK number = N
        Calculate the new CWND size by Eq. (4);
11) Else If No ACK feedback exceeding the timeout
        Retransmit the packet 1 and wait for feedback. Then,
        update Vn and calculate the new CWND size;
12) End if.
```

2.2. Q-Learning Timeout Selection Algorithm

In order to maximize the channel efficiency and improve the network throughput, we use multiple sliding window mechanism to transmit data packets. With the reliable QoS requirements, we employ the selective retransmission scheme to guarantee all the data packets can be received successfully. Due to the time-varying acoustic channel and the various network statuses, the instantaneous data rate is a variable. Thus, the timeout for retransmission need to adjust according to the various acoustic channels. The optimal timeout selection is implemented with a Q-learning algorithm, a model-free method which learns the value of a function $Q(s, a)$ to find the optimal timeout policy for underwater acoustic wireless networks.

Q-learning is based on the value of state-action pairs $Q(s, a)$. We define the value of taking action a in state s under a policy π by $Q^{\pi}(s, a)$ [10]. The state, action, state transition probability, and reward function are defined as follows.

State: The State are defined as the numbers of successful transmission packets N_s minus the numbers of retransmitted packets N_r, denote by N_k and

$$N_k = N_s - N_r \tag{6}$$

The state is denoted by

$$S = \{N_s\} \tag{7}$$

where the value of state depends on the number of transmitted packets.

Action:

$$A = \{a_i\}, i = 1, 2, \ldots., E \tag{8}$$

where E denotes the number of timeout selection. The execution of a_{i} represents that the ith candidate is selected to as the transmitting timeout.

State Transition Probability: Since there are two circumstances of data packet transmissions: successfully transmitted or packet lost. The transition just appears at adjacent states, as shown in Fig. 8. If one packet successfully transmitted, the state will move from state $(K-1)^1$ to state K with probability $1 - P_l(t)$, where $P_l(t)$ is the data packet loss rate at epoch t. If the packet is lost, the state will move from state $(K+1)$ to state K with probability $P_l(t+1)$, which is the data packet loss rate at epoch $(t+1)$. Thus, the transition probability of the state move from the state s_t to the state s_{t+1} under action a can be characterized by the matrix:

$$P^{a}_{S_t+S_{t+1}} = \begin{pmatrix} P_l^{a1}(t) & \cdots & 1-\ P_l^{a1}(t) \\ \vdots & \ddots & \vdots \\ P_l^{aE}(t) & \cdots & 1-\ P_l^{aE}(t) \end{pmatrix} \tag{9}$$

where $P_l^{aE}(t)$ is the packet loss rate under the action a_E at epoch t. Due to the time-varying acoustic channel, the packet loss rate of data transmission is always changing. Thus, we employ the average value to express the packet loss rate.

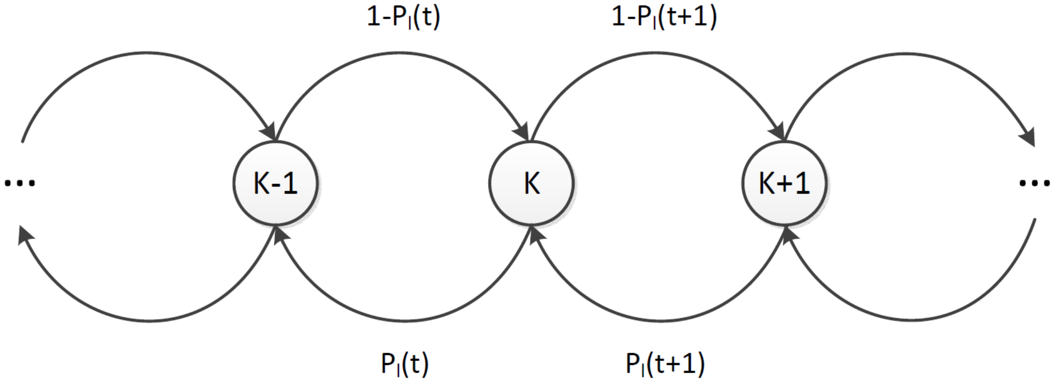

Figure 8. State Transition for data packets transmission.

Reward Function: Since the objective of our proposed Q-learning algorithm is to obtain high network throughput and improve channel utilization while guaranteeing the QoS provisioning for underwater image transmission, we define the reward function for three possible situations, including ACK received, NACK received and packet lost. The reward function represents the performance of the action. The goal of our proposed timeout selection algorithm is to get the optimal timeout for image transmission with maximum reward. Thus, these reward functions are defined respectively:

$$R_t = \begin{cases} w_1(1 - P_l) - w_2 \frac{T_{ack} - T_{to}}{RTT} & ACK\ received \\ - w_2 \frac{T_{nack} - T_{to}}{RTT} & NACK\ received \\ -P_l & Packet\ dropped \end{cases} \tag{10}$$

where T_{ack} , T_{to} , and T_{nack} are the time point when the sender receives ACK, retransmission, and NACK, respectively.

The first equation in Eq. (10) is used to calculate the reward when the data packet transmission is successful. The first term represents the performance improvement on packet loss rate, and the second term represents the channel utilization efficiency, respectively. w_1 and w_2 are the weighting factors for the metrics of packet loss rate and channel efficiency, respectively.

In the Q-learning algorithm, a policy π is mapping from each state $s \in S$ and action $a \in A$ to the probability π (*s*, *a*) of taking action *a* when in state *s*. The value of a state *s* under a policy π, represented by$V^{\pi}(\mathrm{s})$, denoting the expected total reward that can be received under the policy π:

$$V^{\pi}(s) = \mathbb{E}_{\pi}\{\sum_{k=0}^{\infty} \gamma^{k} R_{t+k} \,|s_{t} = s\} \tag{11}$$

where $\mathbb{E}_{\pi}\{\}$ denotes the expected value under policy π, which means the total reward that can be obtained by taking an action at time *t*. γ is the discount factor in the range of (0, 1), which is used for discounting the rewards in the future.

With the above definitions, we can obtain the optimal Q-value of a state, which is determined by the optimal action. Thus, we can get

$$\begin{aligned} V^{*}(s) &= \max\{V^{\pi}(s)\} \qquad (12) \\ &= \max \mathbb{E}_{\pi}\left\{\sum_{k=0}^{\infty} \gamma^{k} R_{t+k} | s_{t} = s\right\} \\ &= \max \mathbb{E}_{\pi}\left\{R_{t} + \gamma \sum_{S_{t+1}} P_{S_{t},S_{t+1}}^{a_{t}} V^{*}(S_{t+1})\right\} \end{aligned}$$

The first term is the immediate rewards achieved by the selected timeout. The second term is the future rewards obtained by the current action, where $\mathrm{P}_{\mathrm{S}_{t},\mathrm{S}_{t+1}}^{\mathrm{a}}$ is defined in Eq. (9).

Based on the Q-learning algorithm, we will get the Q-values as expected reward as the sum of taking an action and the following policy π, represented by:

$$Q(s_{t}, a_{t}) = R_{t} + \gamma \, \sum_{s_{t+1} \in \mathrm{S}} P_{s_{t},s_{t+1}}^{a_{t}} V^{*}(s_{t+1}) \tag{13}$$

where

$$V^{*}(s) = \max\{Q^{*}(s_{t}, a_{t})\} \tag{14}$$

and then, we can derive

$$Q^{*}(s_{t}, a_{t}) = R_{t} + \gamma \, \sum_{s_{t+1} \in \mathrm{S}} P_{s_{t},s_{t+1}}^{a_{t}} \max\{Q^{*}(s_{t+1}, a)\} \tag{15}$$

where $Q^{*}(s_t, a_t)$ is the expected reward that can be received by taking an action a_t at the state s_t following the optimal policy π. It can be derived through the iterations:

$$Q(s_t, a_t) = (1 - a)Q(s_t, a_t) + a[R_t + \gamma \max\{Q^{*}(s_{t+1}, a)\}] \qquad (16)$$

where α is the learning rate, which models the rate of updating Q-values. Therefore, the acoustic system will learn from the time-varying acoustic channels, which can choose the optimal actions to maximize the total rewards.

Assuming in some time epoch of transmission, there are a list of timeout candidates can be selected for the next round transmission, as shown in Table. 1. Thus, a list of anticipate reward for each candidates need to be calculate by Eq. (10), and then we get the reward value list in the second line.

Timeout	1.0	1.2	1.4	1.6	1.8
Reward	3	4	5	4	3

Table 1. Calculate reward for each timeout candidate.

Then, the Q-value for each candidate will be calculated by Eq. (13) and Eq. (14), as shown in Table 2, which is the expected reward as the sum of taking an action and the following policy π.

Timeout	1.0	1.2	1.4	1.6	1.8
Reward	3	4	5	4	3
Q-Value	2	7	4	10	5

Table 2. Calculate Q-Value for each timeout candidate.

Finally, the V-value needs to be updated, as Eq. (14), as shown in Table 3, which is the highest value among all the Q-value.

Timeout	1.0	1.2	1.4	1.6	1.8
Reward	3	4	5	4	3
Q-Value	2	7	4	**10**	5

Table 3. Update V-Value.

The pseudo code of the Q-learning algorithm is listed at Algorithm 2.

Algorithm 2 The Q-learning algorithm

```
1) Begin;
2) Set up the states of image packets transmission;
3) Initialize the V(s) value of all states;
4) Set up an action list of timeout candidates $a_i$;
5) Get the information from acoustic channel feedback and
        decide the status (ACK received, NACK received, or
        Packet lost, see Eq. (10));
6) Calculate the state transition probability;
```

7) Calculate the Q-value of all states through Eq. (13) under all the different actions;

8) Select the maximal Q-value as $V^*(s)$*;*

9) Update the set of $V(s)$*;*

10) Obtain the optimal policy π *and the maximal throughput.*

2.3. Multi-hop Acoustic Communications

We consider a multi-hop string topology network where there is a single sender S and a single receiver D, as shown in Fig. 3. We employ our proposed ARTFEC protocol into multi-hop acoustic communication and transmit the data packet by packet between the S-R link and R-D link, respectively. In Fig. 9, there are 8 procedures to complete the image transmission over multi-hop underwater wireless networks. We explain the process as follows:

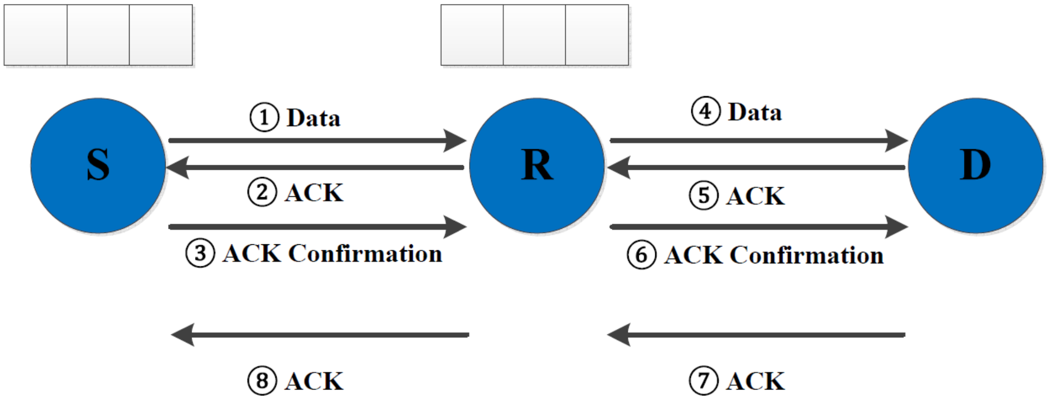

Figure 9. Multiple congestion window for multi-hop image transmissions among the sender S, the relay R and the destination D with eight procedures.

1) The sender S sends multiple data packets with the current window size;
2) The relay R sends ACK to S according to our proposed ARTREC protocol, which including the adaptive congestion window control scheme and the Q-learning timeout selection algorithm, respectively;
3) The sender S sends ACK confirmation to R until S receives the ACK number which is the same as the number of congestion window size, then the first data link between the S and the R is finished. S will update the congestion window size depending on RTT of the current data link;
4) The relay R sends multiple data packets with current window size;
5) The receiver D sends ACK to R according to our proposed ARTREC protocol, which including the adaptive congestion window control scheme and the Q-learning timeout selection algorithm, respectively;
6) The relay R sends ACK confirmation to D until R receive the ACK number same with the number of congestion window size, then the second data link between the R and the D is finished. R will update the congestion window size depending on RTT of the current data link;
7) The receiver D sends ACK to R to tell S send next packets;
8) The relay R sends ACK to S to continue the data transmission.

3. PROTOCOL IMPLEMENTATION

In order to verify the design and evaluate the performance, we implement our proposed ARTFEC on real underwater acoustic network (UAN) nodes. We describe the nodes in both hardware and software platform. As shown in Fig. 10, the hardware platform includes the acoustic OFDM modem, which conducts acoustic communications in underwater acoustic networks, a laptop, which is a controller of the UAN nodes, and three power supplies. The software platform is Aqua-Net [11] protocol stack on Linux system.

Aqua-NET is a layered protocol stack, composed of a physical layer, a MAC layer, a network layer, a transport layer and an application layer [12]. We implement the ARTFEC on the transport layer. For the other layers, we employ image traffic transmission protocol on the application layer, static routing on the routing layer, broadcast MAC on the MAC layer, and the acoustic OFDM modem driver on the physical layer.

Fig. 11 shows an error case when we implement TCP protocol in the transport layer. Since there is no advanced flow and error control mechanism for underwater acoustic transmission, the received image got error because of the disorder of the data packets.

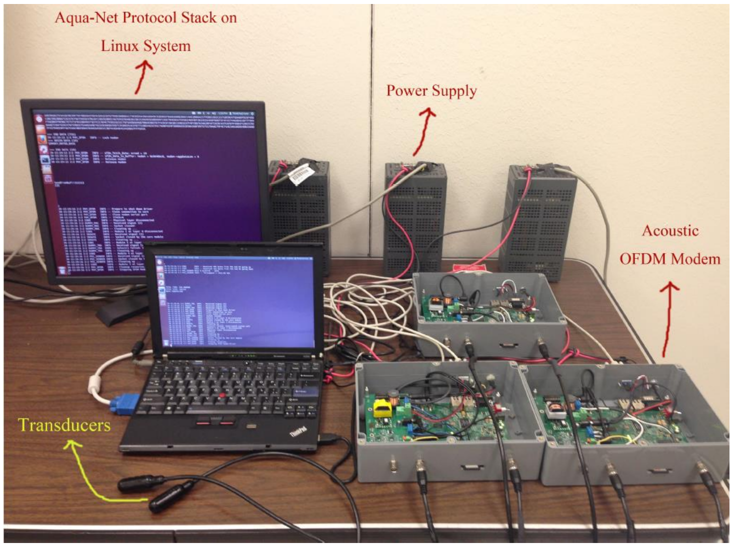

Figure 10. The lab test bed of image transmission using acoustic OFDM modems in underwater wireless networks.

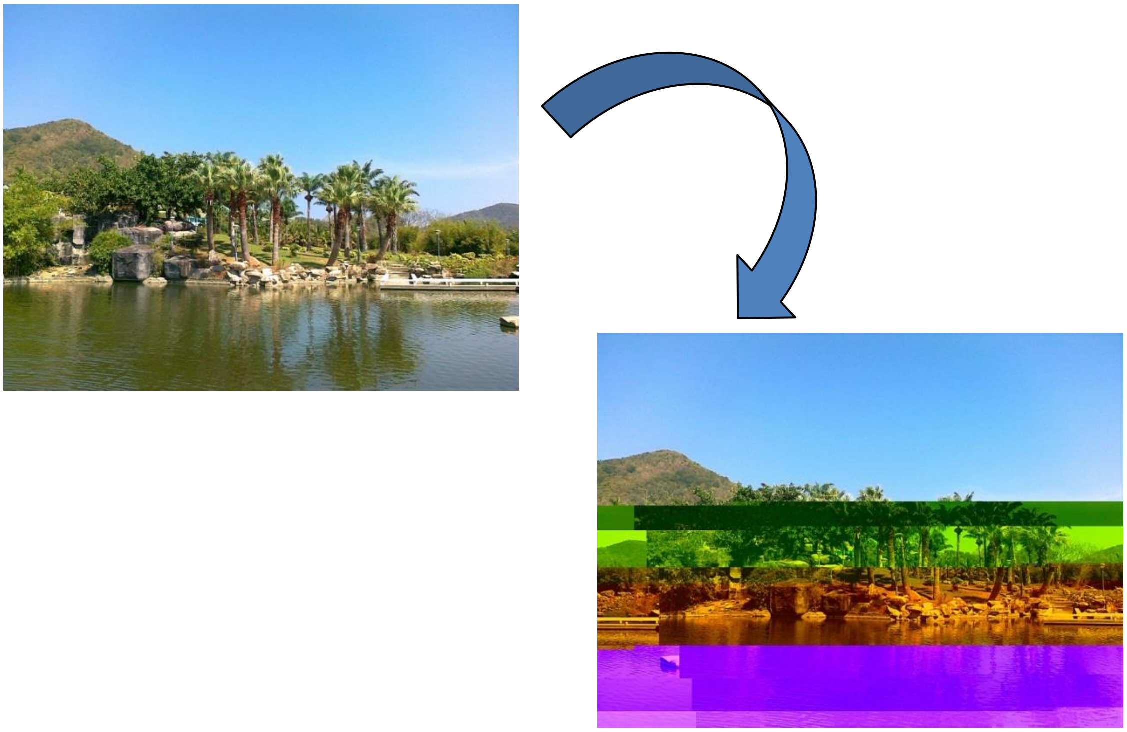

Figure 11. An error case of image transmission using acoustic OFDM modems in underwater wireless networks.

4. TESTBED RESULTS

We conduct experimental tests in our lab testbed, aiming to evaluate the performance of our proposed ARTFEC protocol over multi-hop underwater wireless networks. We implement three different transport layer protocols, which are RDT, TCP, and ARTFEC, respectively. Firstly, we transmit an image with 100 KB (Bytes) over a single-hop acoustic communication to verify the feasibility and performance of our proposed ARTFEC protocol. Then, we transmit the image over multi-hop underwater wireless networks.

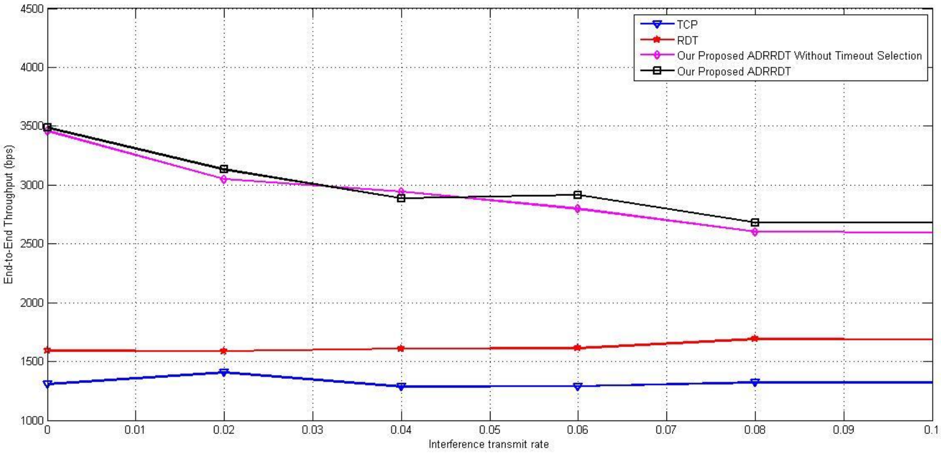

Figure 12. End-to-end throughput with different interference intensities.

Fig. 12 plots the end-to-end throughput performance under various underwater interference intensity for four different reliable transport layer protocols including the ARTFEC, ARTFEC without timeout selection, RDT, and TCP, respectively. As shown in Fig. 12, the performance of ARTFEC and ARTFEC without timeout selection scheme decrease with the increasing interference intensity. The throughputs of RDT and TCP protocols remain low and stable due to their congestion window size is just one. Apparently, our proposed ARTFEC protocol significantly outperforms the other three schemes because we employ the optimal timeout to avoid network congestion and improve the channel utilization.

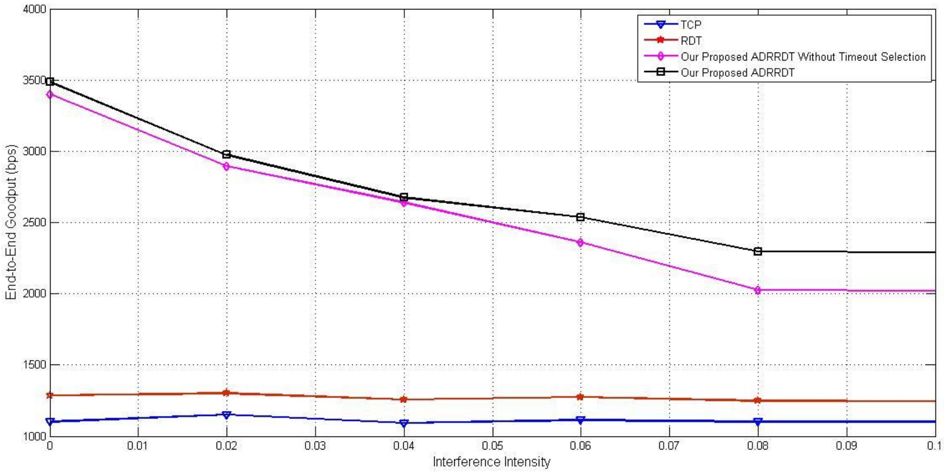

Figure 13. End-to-end goodput with different interference intensities.

Fig. 13 plots the goodput performance under various underwater interference intensity for the four different reliable transport layer protocols including the ARTFEC, ARTFEC without timeout selection, RDT, and TCP, respectively. Fig. 13 shows that the goodput of our proposed ARTFEC protocol decreases when the underwater interference become stronger, which is capable of increasing the packet loss probability. Because our proposed ARTFEC employs the multiple sliding window to transmit the data packets, compared with the single window transmission, there will be a higher goodput decrease. However, our proposed ARTFEC is still superior to other protocols.

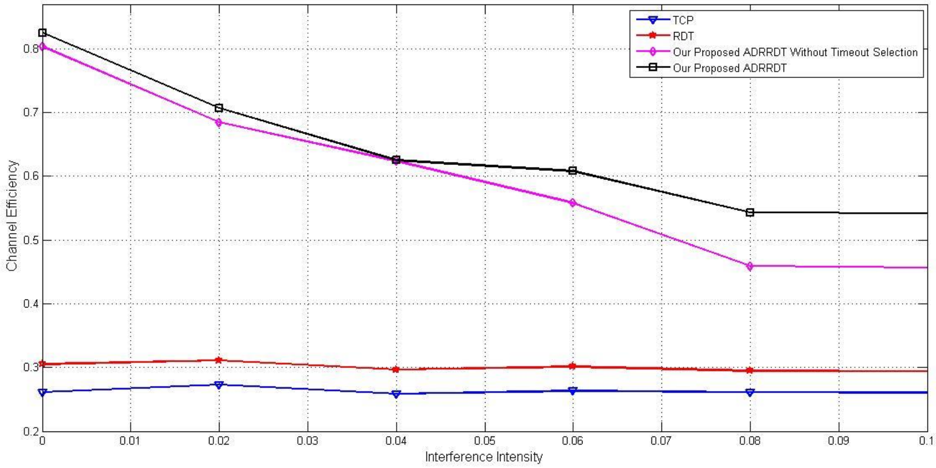

Figure 14. End-to-end channel utilization with different interference intensities.

Fig. 14 plots the acoustic channel utilization performance under various underwater interference intensity for the four different reliable transport layer protocols, respectively. As shown in Fig. 14, our proposed ARTFEC protocol is superior to other protocols because of the use of adaptive congestion window control and the timeout selection algorithm, which gives higher channel utilization. Although the channel utilization decreases as the interference intensity increases, it will become stable when the interference intensity becomes high.

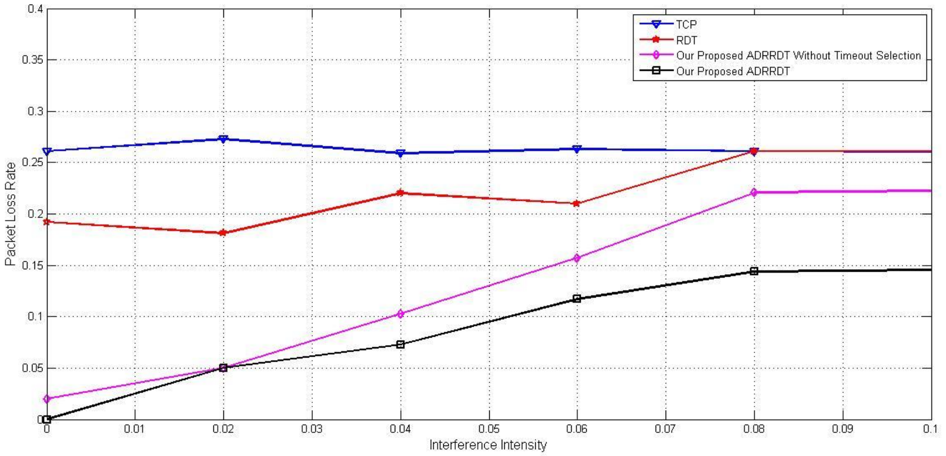

Figure 15. End-to-end packet loss rate with different interference intensities.

Fig. 15 plots the packet loss rate performance under various underwater interference intensity for the four different reliable transport layer protocols, respectively. As shown in Fig. 15, our proposed protocol outperforms the other schemes with the lower packet loss rate, contributed by the adaptive congestion window control and the optimal timeout selection.

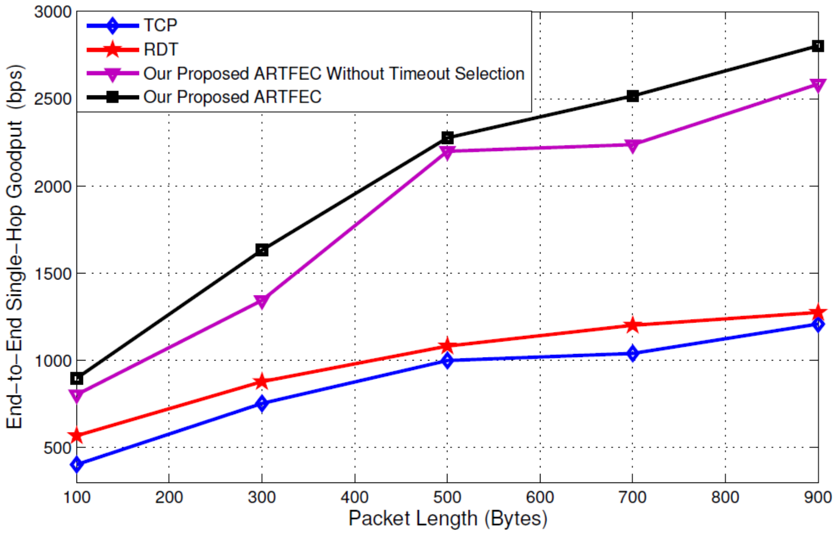

Figure 16. End-to-end single-hop goodput with different packet lengths.

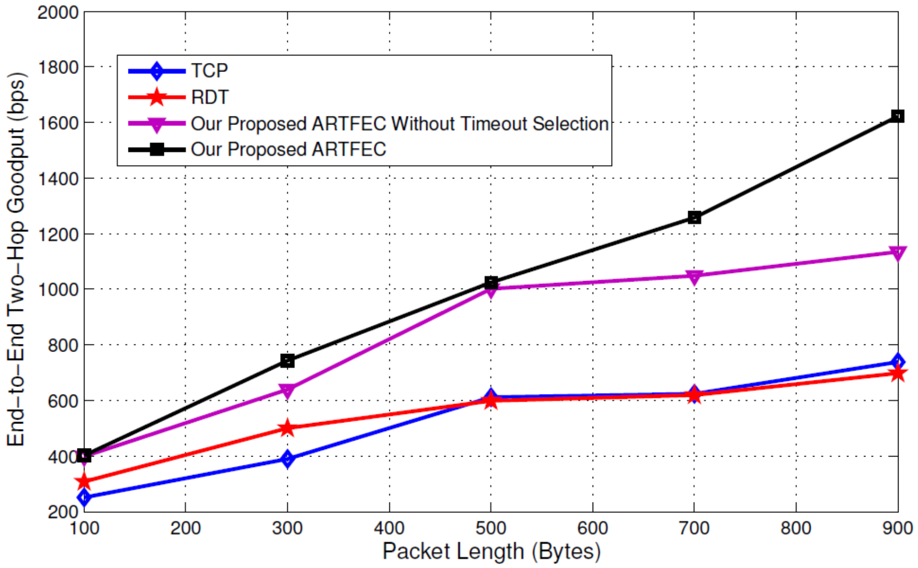

Figure 17. End-to-end multi-hop (two-hop) goodput with different packet lengths.

Fig. 16 and Fig. 17 plot the end-to-end single-hop and multi-hop goodput with different packet lengths under four different reliable transport layer protocols, respectively. As shown in these two figures, the goodput of single-hop and multi-hop increase with the increasing packet length. The multi-hop goodput is one-half of the single-hop goodput since the transmission delay is doubled approximately because of the relay node. However, the multi-hop transmission has better packet loss rate performance and is able to implement image transmission within long distance.

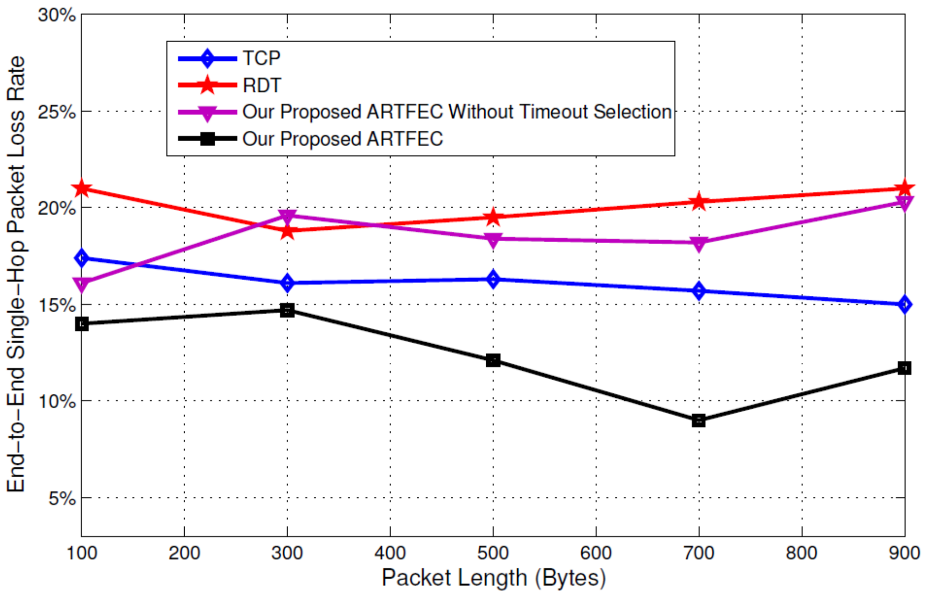

Figure 18. End-to-end single-hop packet loss rate with different packet lengths.

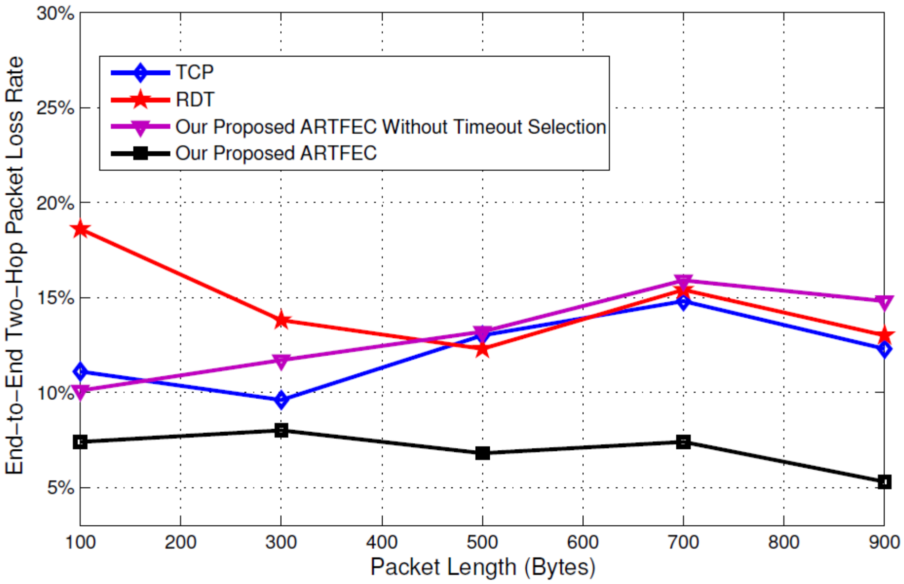

Figure 19. End-to-end multi-hop (two-hop) packet loss rate with different packet lengths.

Fig. 18 and Fig. 19 plot the end-to-end single-hop and multi-hop packet loss rate with different packet lengths under four different reliable transport layer protocols, respectively. As shown in these two figures, the packet loss rates of single-hop and multi-hop are varying randomly as the packet length increases due to the time-varying underwater acoustic channel. However, our proposed ARTFEC protocol has the best performance because of the timeout selection algorithm, especially over multi-hop acoustic communications. In Fig. 18 and Fig. 19, comparing with single-hop transmission, the packet loss rate of multi-hop is decreased by 50% as the result of the relay node added.

5. CONCLUSIONS

Aiming to obtain a high data rate with QoS guaranteed for acoustic wireless communications, we designed, implemented, and analyzed the adaptive RTT-driven transport-layer flow and error control (ARTFEC) protocol for QoS guaranteed image transmission over multi-hop underwater wireless networks. ARTFEC is based on the congestion window size control and the Q-learning optimal timeout selection algorithm with QoS provisioning in order to improve the acoustic network in terms of end-to-end goodput, end-to-end throughput, channel utilization and packet loss rate. We implemented ARTFEC on a lab testbed including the Aqua-Net protocol stack and the acoustic OFDM modems. The testbed results showed that our proposed ARTFEC significantly outperforms the other existing reliable data transmission protocols with QoS provisioning.

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