ICST Transactions on Mobile Communications and Applications Research Article ICST.ORG

Logical Link Control and Channel Scheduling for Multichannel Underwater Sensor Networks

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Abstract

With recent developments in terrestrial wireless networks and advances in acoustic communications, multichannel technologies have been proposed to be used in underwater networks to increase data transmission rate over bandwidth-limited underwater channels. Due to high bit error rates in underwater networks, an efficient error control technique is critical in the logical link control (LLC) sublayer to establish reliable data communications over intrinsically unreliable underwater channels. In this paper, we propose a novel protocol stack architecture featuring cross-layer design of LLC sublayer and more efficient packet-to-channel scheduling for multichannel underwater sensor networks. In the proposed stack architecture, a selective-repeat automatic repeat request (SR-ARQ) based error control protocol is combined with a dynamic channel scheduling policy at the LLC sublayer. The dynamic channel scheduling policy uses the channel state information provided via cross-layer design. It is demonstrated that the proposed protocol stack architecture leads to more efficient transmission of multiple packets over parallel channels. Simulation studies are conducted to evaluate the packet delay performance of the proposed cross-layer protocol stack architecture with two different scheduling policies: the proposed dynamic channel scheduling and a static channel scheduling. Simulation results show that the dynamic channel scheduling used in the cross-layer protocol stack outperforms the static channel scheduling. It is observed that, when the dynamic channel scheduling is used, the number of parallel channels has only an insignificant impact on the average packet delay. This confirms that underwater sensor networks will benefit from the use of multichannel communications.

Keywords: Underwater sensor networks, multichannel communications, cross-layer design, logical link control (LLC), channel scheduling, modeling and simulation, packet delay.

Received on 23 December 2011; accepted on 12 July 2012; published on 03 August 2012

doi:10.4108/mca.2012.07-09.e2

1. Introduction

Underwater sensor networks will play an important role in fulfilling enhanced capability of maritime situational awareness and response in coastal waters. Compared with terrestrial wireless sensor networks, underwater sensor networks experience slower propagation speed, lower transmission rates, and poorer quality of communication links [1–3]. In seawater, for instance, the speed of acoustic signals is in the order of 10^3 meters per second; the data transmission rate for an acoustic modem can be up to a few *kbps* with a transmission range up to several kilometers; high bit error rates (BER) are expected in underwater sensor networks due to multipath interferences and Doppler distortions.

Multichannel technologies have been adopted in next-generation terrestrial wireless communications to increase data transmission rate. For instance, a multiple-input multiple-output antennas (MIMO) system uses multiple channels consisting of distinct antenna pairs [4], while orthogonal frequency division multiplexing (OFDM) applies disjoint frequency bands to form multiple channels [5, 6]. Both technologies have been used in wireless network standards such as WiMax (IEEE 802.16) [7] and LTE (3GPP Long Term Evolution) [8]. Thanks to these developments in terrestrial wireless networks and recent advances in acoustic communications [9–12], the multichannel technologies are used in underwater networks to

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*Corresponding author. Email: jun.li@crc.gc.ca increase data transmission rate over more bandwidth-limited underwater channels.

Given the exceptionally high bit error rates in underwater networks, an efficient error control technique is critical in the logical link control (LLC) sublayer to establish reliable data communications over intrinsically unreliable underwater channels. In comparison to multichannel medium access control (MAC) schemes (e.g., [13–15]) and routing protocols (e.g., [16–18]) reported in the literature for long-delay underwater sensor networks, little research on the LLC design in multichannel underwater sensor networks has been conducted. Indeed, several studies in the context of single-channel underwater communications have been reported [3, 19, 20]. All LLC schemes reported in these studies are modified versions of the stop-and-wait automatic-repeat-request protocol (SW-ARQ), which has long been known to be less efficient than the selective-repeat ARQ scheme (SR-ARQ) in both throughput and delay performance.

In multichannel terrestrial wireless networks, LLC schemes, which are often designed based on these classical single-channel ARQ protocols, (*i.e.*, SW-ARQ, the go-back-N ARQ protocol (GBN-ARQ), and SR-ARQ) and thus referred to as multichannel ARQ, have become an integral part of the LLC sublayer for high-speed multimedia services [21, 22]. In the literature, several studies on multichannel ARQ protocols for terrestrial wireless networks have been reported. For instance, system throughput performance in multichannel ARQ protocols was studied in [23–25]. Chang and Yang [26] analyzed the average packet delay for the three classical ARQ protocols over multiple identical channels (*i.e.*, all channels have the same transmission rate and the same error rate). Fujii and Hayashida and Komatu [27] derived the probability distribution function of the packet delay for GBN-ARQ over multiple channels that have the same transmission rate but possibly different error rates. Ding [28] considered ARQ protocols for parallel channels that possibly have both different transmission rates and different error rates, and derived approximate expressions for their mean packet delay. The resequencing issue in multichannel ARQ protocols was addressed by Shacham and Chin [29], and recently by Li and Zhao [30]. The packet delay distribution function for SW-ARQ over multiple channels was studied in [31] using an end-to-end analytical approach.

Motivated by the approaches applied to LLC designs for terrestrial wireless networks, in this paper we describe a multichannel underwater sensor network system, where each transmitter-receiver pair will be connected by a generic number of forward channels. Given the physical multichannel system, we propose a novel cross-layer protocol stack architecture for multichannel underwater sensor networks. In the proposed cross-layer design, a dynamic packet-to-channel scheduling policy takes advantage of the channel state information and is combined with a SR-ARQ based error control scheme to provide improved network performance. A simplified version of the proposed protocol stack is implemented and the packet delay performance is evaluated using computer simulations.

The main contributions of this paper include a novel cross-layer protocol stack architecture used for multichannel underwater sensor networks. The proposed protocol stack architecture uses a SR-ARQ based design at the logical link control sublayer, can make the channel state information available at the sublayer via cross-layer design. Using the channel state information, a dynamic channel scheduling can be used for simultaneously and more efficiently transmitting multiple packets over parallel channels. Simulation results show that the dynamic channel scheduling approach enhances the performance of multichannel underwater sensor networks over a static channel scheduling case. With the dynamic channel scheduling, the average packet delay increases with the average of error rates of the parallel channels, but decreases with the variance in the error rates; with the static channel scheduling, the average packet delay increases with both the average error rate and the variance in the error rates. In addition, if the average error rate among parallel channels remains fixed, the number of parallel channels has an insignificant impact on the average packet delay when the dynamic channel scheduling is applied. However, the average packet delay is severely affected by the number of parallel channels when the static channel scheduling is used.

The rest of this paper is organized as follows. Section 2 describes a multichannel underwater sensor network and proposes a protocol stack architecture featuring cross-layer design of the logical link control sublayer protocols. The SR-ARQ based logical link control design is proposed in Section 3, followed by a dynamic channel scheduling in Section 4. Simulation results are presented and discussed in Section 5, followed by the final section concluding this study.

2. Multichannel Underwater Sensor Networks

In this section, we describe a multichannel communication model for underwater sensor networks and propose a protocol stack architecture for the sensor node.

2.1. Multichannel Communication Model

Multiple underwater sensors are deployed on the seabed in a choke point where surveillance and reconnaissance of surface vessels and submarines are required. Each sensor is capable of collecting, processing and communicating sensory data acquired from its surroundings to another sensor node or to a more capable communication unit, such as an autonomous underwater vehicle (AUV). As a result, these multiple sensors form an underwater surveillance network. The physical communication device in each sensor node is a multichannel system, *e.g.*, a CDMA system in [32] or a MIMO-OFDM system in [12]. In addition, the physical device can conduct full-duplex data communication, which has been proven feasible in underwater networks using CDMA techniques [32]. Then, for a connected pair of sensor nodes, a multichannel communication is illustrated in Figure 1, where node A will transmit data packets and receive acknowledgements, while node B will receive data packets and transmit acknowledgements. We assume that the forward link (from A to B) consists of M ($M \geq 2$) parallel channels that can transmit data packets simultaneously. Each channel is characterized by a data transmission rate, which is used to characterize the effective channel bandwidth and defined as the number of bits of data transmitted over the channel during a unit of time, and a packet error rate, which characterizes the lossy property of the underwater channel caused by multipath interferences and Doppler distortions. A feedback channel (from B to A) is used for transmitting acknowledgement frames (see Section 3.2) and is assumed to be error-free. The following assumptions are also used in this study.

- The M forward channels have the same transmission rate, and they are slotted in time with one unit (or slot) equal to the transmission time of a packet over a channel, *i.e.*, the transmission rate of each channel is one packet per slot. Meanwhile, it is equal to the transmission time of an acknowledgement frame over the feedback channel.
- The propagation delay of a data packet on a forward channel and the propagation delay of an acknowledgement frame on the feedback channel are the same as given by τ slots. Then the packet round trip time (RTT) equals $2(\tau + 1)$.
- A high-rate cyclic redundancy check (CRC) error-detection code (*e.g.*, a 16-bit polynomial in [33]) is used so that an erroneous packet received over a forward channel can always be detected.
- Packet errors that occur on different channels are assumed to be mutually independent.

2.2. Cross-Layer Protocol Stack Architecture

Each individual sensor node is configured with the protocol stack shown in Figure 2. In a multi-hop underwater sensor network, the upper layer corresponds to the network layer where a route for each source-destination pair needs to be determined. In the simulation study conducted in this paper, which involves only two one-hop neighbors, the upper layer in Figure 2 will act as either a packet generator (in the transmitter) or a data sink (in the receiver). Packets generated at the upper layer are sequentially assigned to integer numbers, referred to as their sequence numbers. All channels share the same set of packet sequence numbers. Below the upper layer is the data link layer, which is composed of the LLC sublayer and the MAC sublayer, and is next to the physical layer. The focus of this work is design of the logical link control sublayer, which is responsible for correcting corrupted packets caused by poor transmission conditions on channels. To that end, a multichannel MAC protocol (*e.g.*, the one in [14]) is assumed in the MAC sublayer responsible for solving the packet transmission problem due to collisions. The physical layer involves channel coding and modulation at the transmitter, and demodulation and decoding at the receiver. Meanwhile, the channel state information, *e.g.*, the bit error rate of each channel, can be assessed in the physical layer. The LLC design to be elaborated in Section 3 provides services to the upper layer and relies on its immediate lower layer (*i.e.*, the MAC sublayer) to perform required functions. Moreover, as a cross-layer design of the LLC sublayer, our proposed LLC design is allowed to access the bit error rate information of physical channels at the physical layer and use this information for packet transmission scheduling, which will be discussed in detail in Section 4.

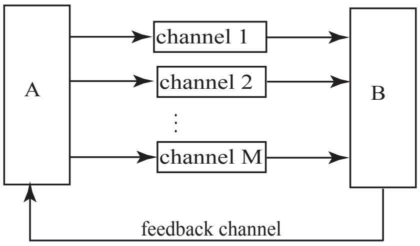


Figure 1. Multichannel Communication Model

3. Logical Link Control Design

In this section, we give an overview of the SR-ARQ scheme for single-channel communications and propose a SR-ARQ based logical link control design for multichannel underwater sensor networks.

For a logical link control sublayer design, each sensor node has a buffer for storing packets. When the sensor node acts as the transmitter, its buffer is referred to as the transmission queue, where packets can wait for transmission and retransmission based on the first-in-first-out service discipline, *i.e.*, packets with

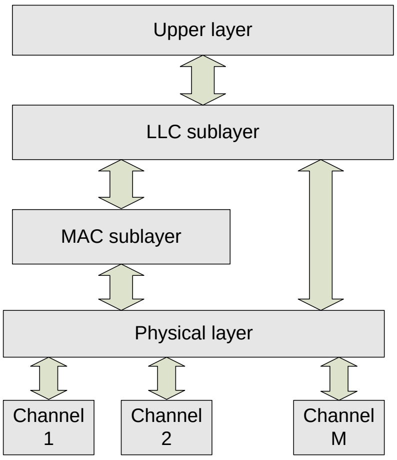


Figure 2. Protocol Stack Architecture

smaller sequence numbers have higher priority to be (re)transmitted than a packet with a larger sequence number. When the sensor node acts as the receiver, its buffer is denoted as the resequencing queue, where out-of-sequenced packets waiting for delivery to the upper layer (e.g., network layer) are temporarily stored.

3.1. SR-ARQ in Single-Channel Communications

In single-channel SR-ARQ, the transmitter sends packets continuously, while the receiver generates either a negative acknowledgement (NACK) for an erroneously received packet or a positive acknowledgement (ACK) for a correctly received packet. These control packets are sent over the feedback channel. Once a NACK arrives at the transmitter, the transmitter retransmits the negatively acknowledged packet without retransmitting the packets following it. To preserve the same order of packets as they arrived from the upper layer, the resequencing queue at the receiver is used to store mis-ordered packets, which are the correctly received packets with the condition that at least one packet with a smaller sequence number has not been correctly received. Via the resequencing queue of the receiver, packets are sequentially delivered from the LLC sublayer to the network layer.

3.2. SR-ARQ Based Multichannel LLC

The M channels are numbered by $i = 1, 2, \cdots, M$. At the beginning of a slot, the transmitter starts transmitting a block of M packets, one packet per channel, and completes transmission at the end of the slot. The receiver receives the block of M packets, which were transmitted in slot t for $t = 1, 2, \cdots$, in slot $t + \tau + 1$ (see Figure 3). The receiver responds to an erroneously received or lost packet by generating a NACK and a correctly received packet by generating an ACK. Then the receiver sends an acknowledgement frame containing the M acknowledgements (ACKs/NACKs) corresponding to the most recently received block of M packets to the transmitter. Transmission of the acknowledgement frame starts at the beginning of slot $t + \tau + 1$ and completes at the end of the slot. After sending the acknowledgement frame, the receiver discards erroneously received packets, delivers the packets in sequence, and stores the out-of-sequenced packets in the resequencing queue.

The transmitter receives the acknowledgement frame, which is associated with the block of M packets transmitted in slot t, in slot $t + 2\tau + 1$. It checks each acknowledgement in the acknowledgement frame, and prepares the next block of M packets to transmit in slot $t + 2(\tau + 1)$ according to the following rule: If there is no NACK in the acknowledgement frame, the next block to be transmitted is composed of M new packets (never transmitted before); if the acknowledgement frame contains k NACKs, the next block of M packets consist of those k negatively acknowledged old packets (transmitted before), and $M - k$ new packets (see Figure 3). Meanwhile, the transmitter removes these positively acknowledged packets from the transmission queue. These selected M packets are to be transmitted in slot $t + 2(\tau + 1)$ according to the channel scheduling policy elaborated in the next section.

4. Dynamic Channel Scheduling Policy

As shown in Figure 2, the proposed LLC design has the knowledge about the current bit error rate of each channel, from which the packet error rate (PER) of the channel can be obtained.

In fact, packet error rate information of channels can be used by the LLC design for scheduling transmission of the block of M packets over the M channels in each slot. We denote the following packet-to-channel scheduling policy by the dynamic channel scheduling. To transmit the block of M packets in a slot, the best channel (*i.e.*, a channel with the smallest error rate) is assigned to the packet associated with the smallest sequence number in the block; the second best channel is assigned to the packet associated with the second smallest sequence number; and so forth. It is noted that, if the communication system uses the same modulation scheme (e.g., M-ary Phase-Shift Keying (MPSK)) for all M channels, which is often true in practice, the dynamic packet-to-channel scheduling policy can be implemented based on the signal-to-interference-plus-noise ratio (SINR) value of each channel. That is, the channel with the largest SINR value is assigned to the packet associated with the smallest sequence number in the block; the channel with the second largest SINR value is assigned to the packet associated with the second smallest sequence number; and so forth. The dynamic channel scheduling is illustrated in Figure 3, where the PER of channel 1 is not greater than that of channel 2 which is not greater than that of channel 3.

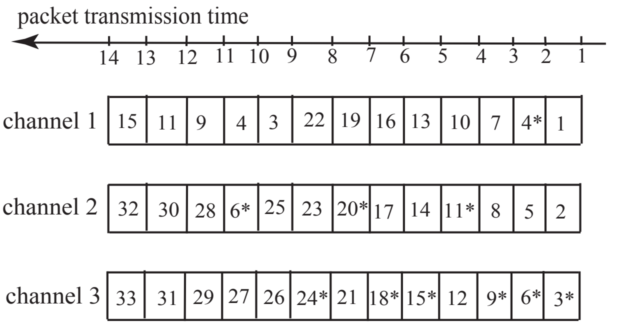
With this approach, the number of out-of-sequenced packets in the resequencing queue is reduced as the number of out-of-sequenced packets incurred by the loss of a packet having a smaller sequence number is always greater than or equal to the number of out-of-sequenced packets incurred by the loss of a larger sequence number packet. For instance, in Figure 3 at the beginning of slot 9, four blocks (packet $1-12$) have been received. In the resequencing queue of the receiver, five packets are out-of-sequenced and waiting. Among them, five packets (i.e., packet $5; 7; 8; 10; 12$) are queued because of the loss of packet 4, four packets (i.e., packet $7; 8; 10; 12$) are queued because of the loss of packet 6, and one (i.e., packet 12) is due to the loss of packet 11. Since correctly receiving the packet associated with the smallest sequence number among the block to be transmitted can lead to immediate delivery of some out-of-sequenced packets in the resequencing queue, this packet should be arranged for transmission with the least possibility for transmission error. As shown in the next section, this dynamic channel assignment will significantly improve the average packet delay performance.

Nevertheless, if the channel bit error rate information is not available in the LLC sublayer, a static channel scheduling can be used to simultaneously transmit a block of M packets over the M channels. The static channel scheduling is illustrated in Figure 4 and works as follows. To transmit the block of M packets in a slot, an old packet (*i.e.*, a packet to be retransmitted) is always assigned to the same channel for retransmission as the originally assigned one, while a new packet (*i.e.*, a packet to be transmitted for the first time) is assigned to a uniformly chosen channel among those available for transmitting new packets. In a real-world multichannel communication environment, a packet to be retransmitted is often assigned to a different channel for retransmission from the previously assigned one due to the time-correlation property of the channel error process. For the time-uncorrelated channels, which are assumed in this study, these two static channel scheduling methods actually have the same effect on the system performance.

As will be shown from simulation results in the next section, the dynamic channel scheduling using the cross-layer design approach outperforms the static channel scheduling.

5. Performance Evaluation

In this section, we conduct a simulation study on the performance of the SR-ARQ based LLC design for multichannel underwater sensor networks. The performance metric that we consider is the average packet delay. The delay of a packet is defined as the amount of time (*i.e.*, the number of slots) between the instant at which the packet is transmitted for the first time and the instant at which it leaves the resequencing queue in the receiver. We investigate the impact of the two channel scheduling policies and the system parameters on the average packet delay performance through simulations.



x* denotes transmission error of packet x;
integer numbers in the boxes are sequence numbers of packets.

Figure 3. Dynamic Channel Scheduling ($M = 3; \tau = 3$)

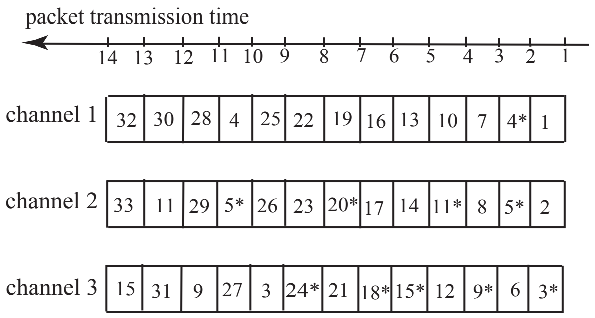


Figure 4. Static Channel Scheduling ($M = 3; \tau = 3$)

5.1. Simulation Environment

We use the SimPy simulator [34], which is an object-oriented, process based discrete-event simulation platform based on the standard programming language Python. SR-ARQ based LLC design is first implemented with SimPy. Then two individual processes, one considered as the transmitter and the other as the receiver, form an M-channel underwater sensor network. Each process independently operates an object of SR-ARQ based LLC. The transmitter continuously sends data packets and receives acknowledgement frames, and the receiver receives data packets and sends out acknowledgement frames. Data packets are transmitted over M parallel channels, while acknowledgement frames are transmitted via a separate feedback channel with no errors.

In the following simulation study, the round trip time of a packet is fixed to be 8 slots, $\tau = 2$. We assume that the packet lossy property of a channel is time-invariant. That is, the probability p_i that a packet transmitted over channel i is erroneously received or simply lost is a real number in $(0, 1)$. Since the channels may have different packet lossy properties, p_i might be different from p_j, for $i, j = 1, \cdots, M$ and $i \neq j$. Without loss of generality, we assume that the channels are ordered according the their packet error rates, *i.e.*, $p_1 \leq p_2 \leq \cdots \leq p_M$. Then, we use Δ_i to represent the ratio of p_{i+1} to p_i for $i = 1, \cdots, M-1$, *i.e.*,

$$\Delta_i = \frac{p_{i+1}}{p_i}, \qquad i = 1, \cdots, M-1. \tag{1}$$

It is clear that, the larger the value of Δ_i, the greater the difference between the error rates of channels i and $i+1$. For this study we let $\Delta = \Delta_1 = \cdots = \Delta_{M-1}$. After letting p denote the average of the error rates for the M channels, *i.e.*,

$$p = \frac{1}{M}\sum_{i=1}^{M} p_i, \tag{2}$$

the triad (M, Δ, p) uniquely determines the packet error rate sequence $(p_1, p_2, \cdots, p_M)$.

5.2. Simulation Results

We plot the simulation results of the average packet delay for the SR-ARQ based LLC with the dynamic and static channel scheduling in Figure 5, Figure 6, and Figure 7. From these plots we observe that the dynamic channel scheduling improves the packet delay performance in multichannel underwater sensor network environments over the static channel scheduling. For instance, for $M = 16$, the average packet delay is reduced by as much as 70% when the packet-to-channel scheduling policy changes from the static channel scheduling to the dynamic channel scheduling. When $\Delta = 1.5$, the average packet delay for the dynamic channel scheduling is only one third of that for the static channel scheduling.

The average packet delay is plotted in Figure 5 for $\Delta = 1.2$, $p = 0.25$, and M varying from 2 to 16. As expected, the average delay difference between the two channel scheduling policies becomes larger with M. Meanwhile, as M increases, the average packet delay with the dynamic channel scheduling slightly increases at first and then slightly decreases. This shows that, under the saturated traffic condition, the overall impact of the number of parallel channels on the packet delay performance is insignificant for this scheduling policy. Since the number of channels has only an insignificant impact on the average packet delay, the use of parallel channels will be a favorable option for packet error control in a multichannel underwater communication system with the SR-ARQ based LLC. It is noted that, for the multichannel LLC design under non-saturated traffic conditions, packet end-to-end delay includes another delay component, the packet waiting time at the transmitter, in addition to the packet delay defined in this study. Under a non-saturated traffic condition, it is clear that the increase of the transmission rate mainly results in the reduction of the packet waiting time at the transmitter, and hence the packet end-to-end delay. So the above observation corroborates the fact that the increase of the number of parallel channels leads to the increase of the transmission rate hence the decrease of the overall packet delay for multichannel underwater communication systems with non-saturated traffic.

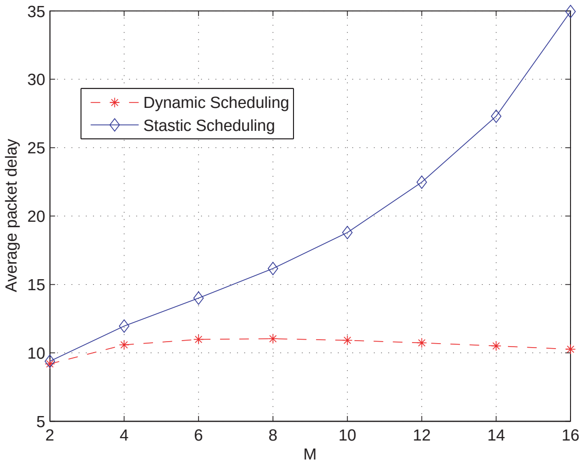


Figure 5. Average Packet Delay vs. M ($\Delta = 1.2$, $p = 0.25$)

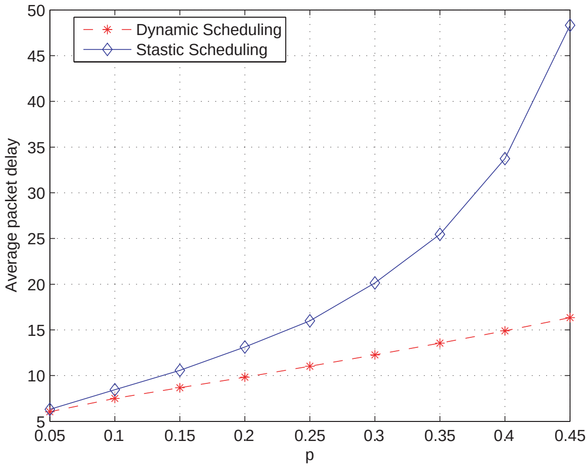


Figure 6. Average Packet Delay vs. p ($\Delta = 1.2, M = 8$)

In Figure 6, we plot the average packet delay when $M = 8$, $\Delta = 1.2$, and p is varying from 0.05 to 0.45. The average packet delay increases as p does, while the increasing rate with the dynamic channel scheduling is

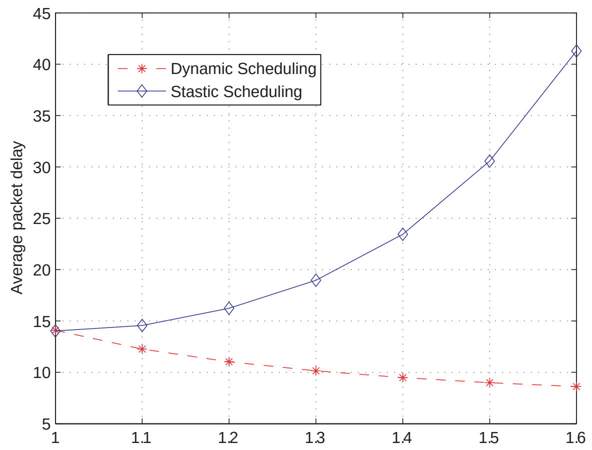


Figure 7. Average Packet Delay vs. Δ ($M = 8$, $p = 0.25$)

smaller than that with the static channel scheduling. The average packet delay is shown in Figure 7 when $M = 8$, $p = 0.25$, and Δ is varying from 1.1 to 1.7. As Δ increases, the average packet delay decreases when the dynamic channel scheduling is applied, but it increases when the static channel scheduling is used. For example, when Δ increases from 1.1 to 1.5, the average packet delay with the dynamic channel scheduling decreases almost by 50%, but the average packet delay with the static channel scheduling increases by 100%. This is explained by the fact that for greater variance in the error rates, the error rates of the first few channels is smaller. For instance, in Figure 7, the error rates of channels 1 to 4 when $\Delta = 1.2$ are smaller than the corresponding ones when $\Delta = 1.1$. Intuitively, the packets transmitted over the first few channels have a higher probability of being correctly received (and delivered to the upper layer). This results in a smaller possibility for the other packets to be queued in the resequencing queue. Therefore, the average waiting time of a packet queued in the resequencing queue is reduced, and so is the total average packet delay.

6. Conclusion

In this paper, we proposed a SR-ARQ based logical link control design for multichannel underwater sensor networks and a cross-layer design of packet-to-channel scheduling policy for more efficient transmission of multiple packets over parallel channels. The dynamic channel scheduling is proposed when channel state information is obtained at the LLC sublayer through the cross-layer design approach, while the static channel scheduling is the option when no channel state information is available at the LLC sublayer. We performed a simulation study on the average packet delay for the proposed LLC design with the two channel scheduling policies. From simulation results, we observed that the dynamic channel scheduling always achieves a better packet delay performance than the static channel scheduling. The average packet delay with the dynamic channel scheduling increases with the average error rate of all channels, but decreases with the variance in the error rates of the parallel channels. More interestingly, we observed that the number of parallel channels has an insignificant impact on the average packet delay, when the dynamic channel scheduling is applied in multichannel underwater communications, and hence the use of parallel channels is a favorable option for multichannel underwater networks.

Acknowledgement. This work reported herein was supported by Defence Research and Development Canada (DRDC).

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