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Implementation of Parallel Multichannel Communications using Stop-and-Wait ARQ

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Abstract: In a parallel multichannel data communication system the stop-and-wait Automatic Repeat Request (ARQ) protocol for parallel channels with an in-sequence delivery guarantee is used for error control. Under the assumption that all channels have the same transmission rate but possibly different time-invariant error rates, we evaluate the probability generating function of the resequencing buffer occupancy and the probability mass function of the resequencing delay. Then, by assuming the Gilbert–Elliott model for each channel the probability mass functions of the resequencing buffer occupancy and the resequencing delay for time-invariant channels are computed. From numerical and simulation results, the mean resequencing buffer occupancy and the mean resequencing delay as functions of system parameters are analyzed. The modeling technique and analytical approach used in this paper can be applied to the performance evaluation of other ARQ protocols over multiple time-varying channels.

Keywords: In-sequence Delivery, Multichannel Data communications, Resequencing buffer occupancy, Resequencing Delay, SW-ARQ

I. INTRODUCTION

AUTOMATIC-REPEAT-REQUEST (ARQ) is an error-control technique widely used in digital data transmission. An ARQ system corrects erroneously received packets through retransmission of packets. The idea of using ARQ strategies was first introduced after which three classical ARQ schemes have been developed: stop-and-wait (SW-ARQ), go-back-N (GBN-ARQ), and selective-repeat (SR-ARQ). In SW-ARQ, the transmitter sends a packet to the receiver and waits for its acknowledgment. Based on error-detection results, the receiver generates either a negative acknowledgment (NACK) or a positive acknowledgment (ACK) for each received packet and sends it over a feedback channel. If an ACK is received, the transmitter sends out a next packet; otherwise, if an NACK is received, retransmission of the same packet will be scheduled immediately, and this process continues until the packet is positively acknowledged. In GBN-ARQ, the transmitter sends packets to the receiver continuously and receives acknowledgments as well. When a NACK is received, the transmitter retransmits the negatively acknowledged packet immediately and all already-transmitted packets following it. In SR-ARQ, the transmitter sends packets continuously until a NACK arrives at the transmitter, in which case the transmitter retransmits the negatively acknowledged packet without resending the transmitted packets following it. To preserve the original arriving order of packets at the receiver, the system has a buffer, referred to as the resequencing buffer, to store the correctly received packets that have not been released. These ARQ protocols for single-channel communications have been extensively studied in the literature, for example, in [1]–[10].Since ARQ protocols achieve reliable transmission of packets over intrinsically unreliable channels such as lossy wireless links, they have been extensively used in the next-generation wireless packet data networks to provide high-speed data integrated with voice services. In a modern high-speed wireless data network, however, multiple parallel channels between adjacent transmitter–receiver pairs are often created using advanced wireless communication technologies systems and multiple-input–multiple-output (MIMO) systems [11] to increase the data transmission rate. Unlike packet transmission over a single channel, in a multichannel communication system, multiple packets are sent at a time, one packet per channel, and packet transmission errors can occur across every channel. To implement error control through retransmission of packets in a multichannel communication system, an ARQ protocol has been generalized to allow concurrent transmission of multiple packets. The performance of the three classical ARQ protocols for multiple identical channels. The average number of packets successfully transmitted per unit of time, and the mean transmission delay, which is the average time between the instant when a packet is transmitted for the first time and the instant when it is successfully received, have been derived. The transmission-delay [12] distribution functions of GBN-ARQ for parallel channels that have the same transmission rate but possibly different time-invariant error rates. Recently, [13][14] the ARQ protocols for parallel channels in which each channel may have a unique transmission rate and error rate. Expressions for the throughput and the mean transmission delay have been derived. In this a resequencing analysis for SR-ARQ over parallel channels, all of which have the same transmission rate but possibly different time-invariant error rates. All of the above mentioned studies on multichannel ARQ protocols have been based on the assumption of a time-invariant error rate for each channel. In a wireless communication system, however, the transmission condition of a wireless channel changes over time, and consequently, the channel is often severely affected by time-varying losses. Even though studies [5]–[11] on ARQ protocols over a single channel of time-varying models have been conducted, there has been no study reported in the literature for analysis of multichannel ARQ protocols with time-varying channel models. In this project, a multichannel SW-ARQ protocol for both time-invariant and time-varying channel models. The performance of the resequencing buffer in terms of the resequencing buffer occupancy, which is the number of packets waiting in the resequencing buffer for delivery, and the resequencing delay, defined as the waiting time of a packet in the resequencing buffer, in steady state. First, under the assumption that all channels have the same transmission rate but possibly different time-invariant error rates, we derive the probability generating function of the resequencing buffer occupancy and the probability mass function of the resequencing delay. Then, when a traditional time-varying channel model, the Gilbert–Elliott model [15], is assumed, the pgf of the resequencing buffer occupancy and the mean resequencing delay. Through examples, compute the pmf of the resequencing buffer occupancy, from which we demonstrate that the pmf of the resequencing buffer occupancy can be efficiently obtained from its pgf by using the Lattice–Poisson algorithm [16], and the pmf of the resequencing delay. From plots of numerical and simulation results, the mean resequencing buffer occupancy for both time-varying and time-invariant channels benefits from the dynamic assignment rule. In addition, the mean resequencing buffer occupancy and the mean resequencing delay for both channel models grow with the increase of either the number of channels or the average error rate of channels. They decrease, however, with the increase of the variance in the error rates. That is, when the time-invariant channel error rates are assumed, the mean resequencing buffer occupancy and the mean resequencing delay decrease as the error rates of different channels become more different. Likewise, in Gilbert–Elliott model, decreasing the two error states become more different from each other. The main contributions of this Project include modeling and exact probabilistic analysis of the resequencing buffer occupancy and the resequencing delay for SW-ARQ over parallel channels of both the Gilbert–Elliott model and the model with time-invariant error rates. The obtained pgf and pmf lead to an efficient computation of the distribution functions as well as the means of the resequencing buffer occupancy and the resequencing delay, based on which performance properties are derived to provide guidelines for system design and optimization. The modeling technique and

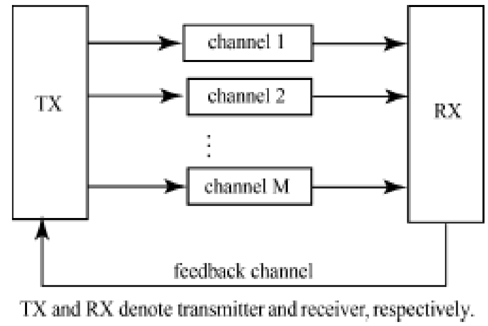

Fig.1. A Multichannel system with ARQ

analytical approaches are expected to be applied to performance analysis of SR-ARQ over parallel channels with time-varying channel models in our future studies. The rest of the paper is organized as follows. Section II describes a system model, a multichannel SW-ARQ protocol and the channel models. The resequencing buffer occupancy and the resequencing delay for channels with time-invariant error rates are analyzed, and resequencing analysis for the Gilbert–Elliott model is presented in next section the Numerical and simulation results are presented and discussed in Section III, followed by the final section containing conclusions and possible future work presented in Section IV.

II. THE MODEL

In terms of the open system interconnection (OSI) reference model for layered network architectures[17], an ARQ protocol is usually located at the link layer (i.e., layer 2). Below and above it are the physical layer (layer 1) and the network layer (layer 3), respectively. In the ARQ protocol point of view, the physical layer provides forward channels (for data packets from the transmitter to the receiver) and feedback channels, and the network layer provides data packets for transmission.

A. A Multichannel System with ARQ

A multichannel data communication system, in which a transmitter–receiver pair communicates data packets, is illustrated in Fig. 1. The communication link between the transmitter and the receiver consists of parallel channels numbered from 1 to M. Each channel, for, is characterized by a data transmission rate and a channel model. The data transmission rate of a channel is measured by the maximum number of packets that can be transmitted over the channel during a specified time period, and the channel model describes the statistical property of transmission errors when packets are transmitted over the channel. Two channel models (to be discussed in Section II-C) will be considered in the study. We assume that packet errors occurring in one channel do not depend on the situations of the other channels. In addition to the (forward) parallel channels, a high-rate cyclic redundancy check (CRC) error-detection code [18] and a feedback channel are provided in the system. We assume that errors of a packet can always be detected and the feedback channel is error-free for transmitting acknowledgment packets. Each data packet in the system is identified by a unique integer number, referred to as the sequence number. The transmitter has a buffer, referred to as the transmission queue,

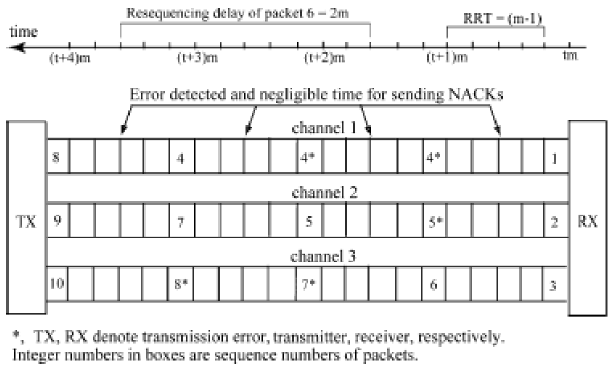

Fig. 2. MSW-ARQ-inS ($M = 3, m = 5$).

to store packets waiting for transmission or retransmission. A buffer, referred to as the resequencing buffer, is provided at the receiver to temporarily store correctly received packets for which at least one packet with a smaller sequence number has not been received without an error. Both the transmission queue and the resequencing buffer are assumed to have an infinite capacity of waiting spaces. The transmission queue is assumed to have an infinite supply of packets, referred to as the heavy-traffic condition in relative studies. All channels have the same transmission rate, and the channels are time-slotted with one unit equal to the transmission time of a packet over a channel. Thus, the transmission rate of each channel is one packet per slot. When transmitted from the transmitter to the receiver, all packets have a fixed round-trip time (RRT) equal to slots, with being a positive odd integer (Fig. 2). The time for a packet to spend on a forward channel is slots. Once packet transmission starts, the transmitter sends multiple packets at a time, one per channel. All channels share the same set of sequence numbers of the packets in transmission and retransmission assignments. A multichannel SW-ARQ protocol with an in-sequence delivery guarantee (MSW-ARQ-inS), operates in the system for packet error control.

B. *MSW-ARQ-inS*

MSW-ARQ-inS, where the transmitter only retransmits erroneously received packets but the receiver delivers packets in the order of their sequence numbers

- At the beginning of a slot, the transmitter starts sending a block of packets to the receiver, and completes its transmission at the end of the slot. Before the transmitter sends the next block of packets in slot, it is idle.
- The receiver receives the block of packets at the end of slot. Each packet is received erroneously with some probability. For channels with time-invariant error rates the probability is for channel, and for channels with time-varying error rates, it is the state of the Markov chain at the instant when the packet is received. After the error detection, the receiver sends an acknowledgment packet, which contains exactly acknowledgments (ACKs/NACKs) corresponding to the most recently received block of packets, to the transmitter.
- The receiver deletes all erroneously received packets, delivers all qualified packets from the resequencing buffer to the upper layer, and stores all unqualified packets for future delivery. A qualified packet is a correctly received packet with a sequence number such that all packets with a smaller sequence number have been correctly received, and an unqualified packet is a correctly received nonqualified packet.
- The transmitter receives the acknowledgment packet at the end of slot . It checks the acknowledgments in the acknowledgment packet, and prepares the next block of packets to transmit according to the following rule. If no NACK is contained in the acknowledgment packet, the next block of packets to be sent are composed of all packets that will be transmitted for the first time. If the acknowledgment packet contains one or more, say NACKs, however, the next block of packets consist of all (old) packets, which are negatively acknowledged by the receiver, and new packets. New packets chosen to be transmitted in the next block are those with the smallest sequence numbers waiting in the transmission queue.
- To transmit the next block of packets in slot, a packet-to-channel assignment rule needs to be specified.

There are two assignment rules, the *static* assignment rule and the *dynamic* assignment rule, to be considered. For the static assignment rule, an old packet is always retransmitted over the same channel as the original assigned one until it is correctly received and new packets selected to be transmitted are randomly assigned to the channels that have successfully transmitted packets in slot.

C. Channel Models

We consider two types of channels, iid channels and Markov channels. In the former case, the transmission error over a channel is characterized by a time-invariant error rate in (0,1) representing the probability that a packet is erroneously received when transmitted over the channel. In the latter case, the packet-error property over a Markov channel is characterized by the Gilbert–Elliott model [15] in which a two-state Markov chain, referred to as the error process, is defined. The state space of the Markov chain is where the two real numbers represent the packet error rates of the channel when it is in good and bad transmission conditions, respectively. The transition matrix of the Markov chain is the Markov chain has the stationary distribution given by .The purpose of this study is to carry out an analysis of resequencing buffer occupancy and resequencing delay for MSW-ARQ-inS. The resequencing buffer occupancy is defined as the number of packets that have been correctly received but not been delivered from the resequencing buffer to the upper layer at the beginning of a slot during which a block of packets are received, and the resequencing delay of a packet is measured from the time epoch at which the packet is successfully received until the epoch of its in-sequence delivery The condition under which the system eventually enters the steady state is trivially satisfied. Under this condition, we conduct the steady-state analysis for MSW-ARQ-inS over iid channels and Markov channels in the following two sections. Our steady-state analysis is based on the dynamic assignment rule, and simulation results of the average resequencing buffer occupancy for the static assignment rule for performance comparisons.

III. NUMERICAL AND SIMULATION RESULTS

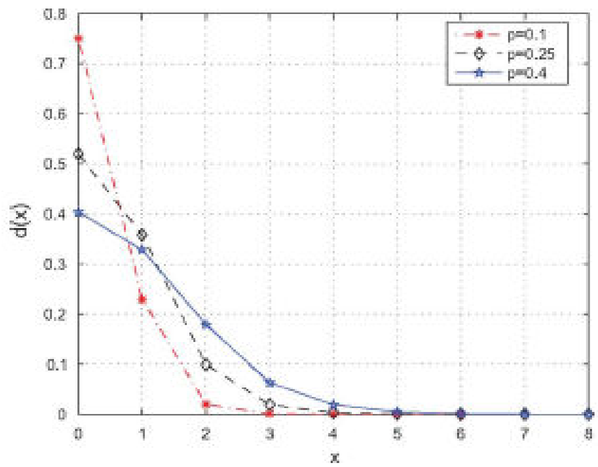

Fig.1 Probability Mass Function

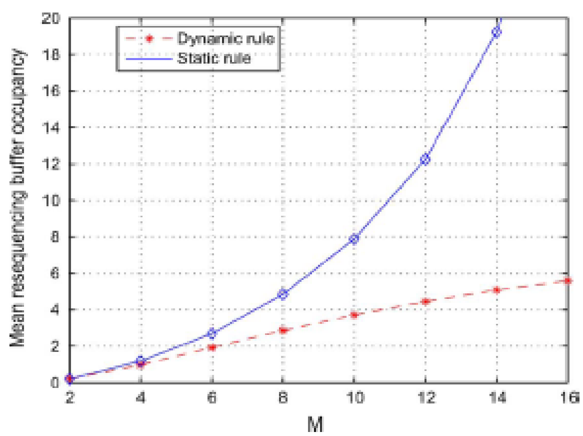

Fig.2.Average Resequencing buffer occupancy

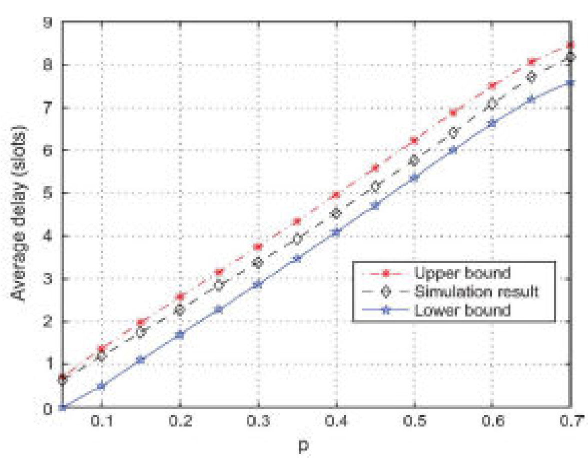

Fig.3. Simulation Result of E [D_r]

This model works in exactly the same way as the model multiplexed in frequency or code, except that a block of M packets are transmitted sequentially during the same time slot instead of being transmitted simultaneously. To model this multichannel system, we make the following modification. The receiver receives the block of packets one by one in subsequent slots. After the receipt of each packet, all qualified packets, if there are any, are delivered to the upper layer immediately, although only one acknowledgment packet that contains acknowledgments (ACKs/NACKs) is sent to the transmitter per slots the average resequencing delay of obtained from simulation, together with its upper and lower bounds for different values of the average (from 0.05 to 0.7). The simulation result confirms our conclusion; that is, the mean resequencing delay is between its lower and upper bounds.

IV. CONCLUSION AND FUTURE WORK

The performance analysis of the resequencing buffer for SW-ARQ-inS over a generic number of parallel channels with both time-varying and time-invariant packet error rates are conducted. With the dynamic assignment rule applied in the protocol, exact statistical results of the resequencing buffer occupancy with both channel models were derived in steady state. The distribution function of the resequencing delay for the model with time-invariant error rates and the mean resequencing delay for the model with time-varying error rates were also obtained. For the model with time-invariant error rates, we numerically computed the pmf of the resequencing buffer occupancy using its probability generating function and the pmf of the resequencing delay. Through numerical and simulation results, the impact of the packet-to-channel assignment rules, the variance in the error states, the average error rate, and the number of parallel channels on the mean resequencing buffer occupancy and the mean resequencing delay are discussed. The dynamic assignment rule always outperforms the static assignment rule for both channel models. For MSW-ARQ-inS over parallel channels with both possibly different time-invariant error rates and the Gilbert–Elliott model, the mean resequencing buffer occupancy and the mean resequencing delay increase with the average error rate and the number of parallel channels even though the mean resequencing buffer occupancy decreases with the variance in the error states. In future work, we can apply the modeling and analytical approach presented in this paper to conducting performance studies on the selective-repeat ARQ protocol over parallel channels with time-varying channel models.

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