Optimization of a Data Link Protocol for an Underwater Acoustic Channel

Milica Stojanovic
Massachusetts Institute of Technology
Cambridge, MA 02139
millitsa@mit.edu

Abstract— **Acoustic modems typically operate in half-duplex, which limits the choice of a data link control protocol to the Stop and Wait (S&W) type. Unfortunately, on channels with poor quality and long propagation delay–such as the majority of acoustic channels–S&W protocol has low throughput efficiency. The basic S&W can be improved by using a modification in which packets are transmitted in groups and acknowledged selectively. Throughput efficiency can now be maximized by selecting the optimal packet size, which is a function of range, rate, and error probability. Quantitative analysis for typical acoustic links shows that modified S&W protocols offer good performance, provided that packet size is chosen close to optimal. In addition, as the group size increases, sensitivity to packet size selection is reduced. To ensure best ARQ performance in mobile acoustic systems where link conditions vary with time, future generation of acoustic modems must focus on adaptive selection of protocol parameters.**

I. INTRODUCTION

With the advent of acoustic modem technology, the number of applications in which underwater sensors and robots are connected through a communication network is growing. One such application, which directly motivated this work, is the search for deep-sea hydro-thermal vents by a small group of autonomous underwater vehicles (AUVs). This project, currently under way at the Woods Hole Oceanographic Institution, focuses on a scenario illustrated in Fig.1. The vehicles are equipped with the acoustic modems [1], which operate in one of two modes: low or high rate (on the order of a hundred or a thousand bits per second, respectively). By enabling a communication between vehicles and the mother ship, the efficiency of search is greatly enhanced. Two types of signals are typically needed: control, status and navigation information, which can be exchanged at low rate, but requires high reliability, and data, such as image information, which requires high rate, but has relaxed requirements on reliability.

The majority of underwater acoustic channels are characterized by a poor quality physical link, caused by time-varying multipath propagation and motion-induced Doppler distortion. As a result, the bit error rate (BER) of an acoustic link is often high. Moreover, it can vary with time as the propagation conditions change. Errors in the received bit stream are thus inevitable, and to establish *reliable* communication over such a channel, an automatic repeat request (ARQ) procedure must be in place by which erroneously received data packets are retransmitted. In general, this procedure can be implemented on the data link layer or on the transport layer of the network architecture. The former is a better choice for poor quality physical links where frequent retransmissions are expected.

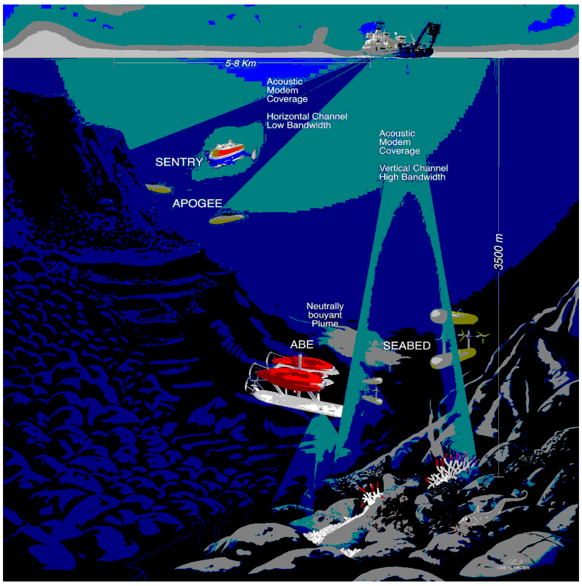

Fig. 1. Several AUVs connected through an acoustic communication network.

The task of the data link control (DLC) is to format the packets and to implement an ARQ protocol. Packet formating includes addition of error control bits, typically in the form of a cyclic redundancy check (CRC). These bits are used at the receiver to check for errors. A packet is found erroneous if it fails the CRC test. The task of an ARQ protocol is to organize retransmission of erroneously received packets. A retransmission can be performed as many times as necessary, until a packet is declared correct (in practice, a limit is imposed on the maximal number of retransmissions). The design and analysis of data link protocols for use with an underwater acoustic system are the focus of this work, whose goal is to develop a protocol that is as efficient as possible, but simple to implement.

The simplest ARQ protocol is the Stop and Wait (S&W) protocol. In this protocol, the transmitter sends a packet and waits for the acknowledgment (ACK). If the ACK does not arrive in a pre-specified amount of time, called the time-out, or a negative acknowledgment arrives, the packet is retransmitted. When the ACK arrives, the transmitter moves on to a new packet. The S&W protocol is well suited for half-duplex operation, which is the mode typically supported by current acoustic modem technology. However, it has poor efficiency on links where the propagation delay is long compared to the packet size (which notably is the case for underwater acoustic channels). The efficiency of an ARQ protocol is measured by the time spent in waiting, and it can be improved if the idle interval between packet transmissions is used to transmit new packets. This is the idea behind the continuous transmission protocols–the Go Back N and the Selective Repeat Protocol [2]. However, as the acknowledgments arrive while new packets are being transmitted, these protocols require full-duplex operation. Hence, despite its low efficiency, S&W protocol appears to be the method of choice for current implementations (e.g., [3]).

To satisfy the half-duplex requirement, but increase the efficiency of the S&W scheme, several versions of this method have been proposed in the past [4]-[7]. These protocols focus on transmission of blocks of packets, rather than a single packet, thus making better utilization of the time spent in waiting for the acknowledgments.

The efficiency of the S&W protocol depends on the packet size, the link delay, and the packet error rate in such a way that there exists an optimal packet size for which the efficiency is maximized [2]. In a terrestrial wireless channel, this optimization is mostly influenced by the link quality, i.e. BER, as the link delay is negligible. In a satellite channel, the link delay becomes significant due to the long distance traveled. In underwater acoustic channels, the ARQ efficiency is limited by both the poor BER performance and the long delay, which is caused here by the low speed of sound propagation (1500 m/s) rather than by long distance. Hence, the worst properties of both radio worlds–poor quality of terrestrial links and high latency of satellite links–seem to combine in an underwater acoustic channel, casting the problem of data link protocol optimization in a new framework.

The practical significance of the fact that it is possible to maximize efficiency of an ARQ scheme by controlling the packet size has been recognized recently, and several algorithms for adaptive adjustment of the packet size in systems where link conditions vary with time have been proposed [8]-[10]. The main idea of these algorithms is to estimate the instantaneous BER and adjust the packet size accordingly (the propagation delay is usually neglected, as these algorithms are suited for terrestrial radio channels). In [8] and [9] a previously-constructed look-up table is used to select the packet size from several available values, while the method of [10] is fully adaptive. Simulation studies show that significant improvement can be achieved on channels whose instantaneous BER is highly variant (e.g., Rayleigh fading channels). Adaptive packet size adjustment has also been considered for optimizing *routing* efficiency [11], which represents another aspect of cross-layer network optimization.

In this paper, statistical analysis of protocol efficiency is carried out for a class of S&W protocols, leading to the optimal packet size which is evaluated as a function of range, bit rate, and expected bit error probability for typical underwater channels. The paper is organized as follows. In Sec.II, an overview of S&W protocols is given. Sec.III contains optimization analysis, whose results are discussed in Sec.IV. Finally, Sec.V summarizes the conclusions.

II. OVERVIEW OF STOP AND WAIT PROTOCOLS

Several variants of the basic S&W retransmission strategy have been proposed over the years, with the common goal of increasing the throughput efficiency. Among the first versions is Sastry's scheme [4] in which whenever a retransmission is needed, not one, but several copies of the same packet are sent. Another retransmission is then needed only if *all* copies are received in error; otherwise, a new packet may be sent. In this manner, the delay caused by repeated transmissions is reduced. This scheme was generalized in [5] where a different number of copies is used for each new retransmission. In essence, these schemes represent a form of repetition coding.

In a version due to Morris [6], the transmitter sends a group of M packets and waits for the acknowledgment. The receiver checks each packet individually and sends the acknowledgments in a group. Those packets that are negatively acknowledged are placed in the new group of M packets for transmission during the next cycle. In this manner, as many as M packets can be transmitted during one round-trip time, and, hence, the throughput efficiency is increased. However, if ordered delivery of packets to the upper layer is needed, the receiver has to store the packets until they can be rearranged. In the scheme proposed by Turney [7], the transmitter also sends out a group of M packets and waits for the acknowledgment, but only those packets that are negatively acknowledged are retransmitted in the next cycle, i.e. no new packets are added. The receiver now does not need the capability to buffer more than M packets for ordered delivery.

Additional improvement of a retransmission strategy can be achieved by dedicated design of an error correction code (hybrid ARQ) and packet combining, whereby the receiver does not discard erroneously received copies of a packet, but uses them to achieve a form of time-diversity and exploit the coding gain.

We focus here on three types of S&W protocols: the basic S&W protocol, called S&W-1, and the two protocols [6] and [7] which involve group transmission of up to M packets, called S&W-2 and S&W-3, respectively. Obviously, S&W-1 represents a special case of either S&W-2 or S&W-3 when M=1.

We assume that each packet consists of a total of $N = N_d + N_{oh}$ bits, where N_d is the number of data bits, and N_{oh} represents packet overhead. At a minimum, N_{oh} equals the number of bits used for CRC. Thus, the packet duration is $T_p = NT$, where $T = 1/R$ is the bit (symbol) duration and R is the bit (symbol) rate. Each group of packets (or each packet if transmitted alone) is preceeded by a synchronization preamble of duration T_{sync}.

The communication link introduces a propagation delay $T_d = l/c$, where l is the distance between the transmitter and receiver, and c=1500 m/s is the nominal speed of sound underwater. Thus, the total time needed for transmission of a group of m packets and reception of the corresponding group of acknowledgments is

$$T(m) = m(T_p + T_{ack}) + T_w \tag{1}$$

where

$$T_w = 2(T_{sync} + T_d) \tag{2}$$

is the total waiting time, and the duration of an acknowledgment is usually negligible with respect to the packet duration, $T_{ack} << T_p$.

For best efficiency, the time-out of an S&W protocol transmitting a group of m packets should be equal to the round-trip time $T(m)$. For simplicity of analysis, we assume that this is the case, keeping in mind that a slightly greater value will be used in practice.

A. S&W-1

The throughput efficiency of an ARQ protocol is defined as the ratio of useful packet time and the total time spent on the average for a successful packet transmission. The average is taken over the number of retransmissions. If by p we denote the probability of packet error, the average time needed to transmit one packet successfully using S&W-1 is given by [2]

$$T_1 = \frac{1}{1-p} T(1) \tag{3}$$

The efficiency is obtained as

$$\eta_1 = \frac{N_d T}{T_1} = (1-p)\frac{N_d T}{T(1)} \tag{4}$$

B. S&W-2

The S&W-2 protocol can be regarded as M S&W-1 protocols operating in parallel. Each S&W-1 has a time-out equal to $T(M)$, and a packet error rate is still equal to p. Hence, the average time needed to successfully transmit a packet on one of M links is $T(M)/(1-p)$. Because the M links operate in parallel, a total of M packets are transmitted successfully during this time. The resulting throughput efficiency is

$$\eta_2 = (1-p)\frac{M N_d T}{T(M)} \tag{5}$$

C. S&W-3

The S&W-3 protocol starts out by transmitting a group of M packets. The time-out is set to allow for the round-trip $T(M)$. At the end of the time-out, one of the following situations will occur: no packets have been successfully received, and the transmitter remains in state "M" with M packets to transmit; one packet has been successfully received, and the transmitter moves into the state "M-1" with M-1 packets left to transmit, etc. When the transmitter is in state "m" ($m \leq M$) the situation is similar. Now, the time-out is set to $T(m)$, and upon receiving the acknowledgment, the receiver moves into the state "$m - k$" if k out of m packets have been positively acknowledged. The probability of this event is $\binom{m}{k} p^{m-k}(1-p)^k$. If we denote by T_m the average time spent in state "m" then the following relation must hold:

$$T_m = \sum_{k=0}^{m} \binom{m}{k} p^{m-k}(1-p)^k [T_{m-k} + T(m)] \tag{6}$$

This relation can be used to find the average time T_M needed for successful transmission of a group of M packets. Setting the initial value $T_0 = 0$, recursive evaluation of the above expression gives

$$T_M = \frac{1}{1-p^M}\left[\sum_{m=1}^{M-1} \binom{M}{m} p^{M-m}(1-p)^m T_{M-m} + T(M)\right] \tag{7}$$

The protocol efficiency is now obtained as

$$\eta_3 = \frac{M N_d T}{T_M} \tag{8}$$

Although there is no closed form expression for the throughput efficiency of S&W-3, it is intuitively obvious that $\eta_2 \geq \eta_3 \geq \eta_1$ (with equality for $M = 1$).

III. PACKET LENGTH OPTIMIZATION

Throughput efficiency given in (4), (5) and (8) depends on the normalized waiting time $T_w/N_d T$ and the packet error probability p. The probability of a packet error is given in terms of the bit (symbol) error probability P_e as

$$p = 1 - (1 - P_e)^N \approx N P_e \tag{9}$$

where the approximation is valid for $P_e << 1$, and we have assumed that bit errors occur independently. By increasing the packet size, better utilization of the waiting time is achieved, but the chances of having a bit error in a packet are increased. Hence, there is an optimal packet size for which the throughput efficiency is maximized. While the bit error rate is determined by the channel conditions and the modulation/detection method used at the physical layer, the packet size can be varied to maximize the efficiency.

The optimal packet size can be evaluated in closed form for S&W-1 and S&W-2 (for S&W-3 it can be found numerically). To do so, it suffices to focus on the expression (5) for η_2 (η_1 is its special case). The efficiency η_2 is expressed in terms of the packet size N_d for given physical layer parameters P_e, R, and the link distance l, as

$$\eta_2 = (1 - P_e)^{N_d + N_{oh}} \frac{N_d}{N_d + \mu} \tag{10}$$

where

$$\mu = N_{oh} + \frac{T_w R}{M} = \mu_0 + \frac{2}{Mc} l R \tag{11}$$

Treating the packet size as a continuous variable, its optimal value is obtained as the solution to $d\eta_2/dN_d = 0$, given by

$$N_{d,opt} = \frac{\mu}{2}\left[\sqrt{1 + \frac{4}{\mu\rho}} - 1\right] \tag{12}$$

where

$$\rho = \ln \frac{1}{1 - P_e} \approx P_e \tag{13}$$

with the approximation valid for $P_e << 1$. This packet size achieves the maximal throughput efficiency

$$\eta_{2,max} = (1 - P_e)^{N_{d,opt} + N_{oh}} \frac{N_{d,opt}}{N_{d,opt} + \mu} \tag{14}$$

When $\mu\rho << 1$, this result can be simplified by the following approximations:

$$N_{d,opt} \approx \sqrt{\frac{\mu}{\rho}} \tag{15}$$

$$\eta_{2,max} \approx e^{-\rho N_{oh}} e^{-\sqrt{\mu\rho}} \frac{1}{1 + \sqrt{\mu\rho}} \approx 1 - 2\sqrt{\mu\rho} \tag{16}$$

We note that the efficiency η_2 increases with the group size M. A practical limit on M will be determined by system constraints such as storage capacity. Nonetheless, it is interesting to note that the upper bound on throughput efficiency is

$$\lim_{M \to \infty} \eta_{2,max} \approx 1 - \sqrt{N_{oh} P_e} \tag{17}$$

for $N_{oh} P_e << 1$. Hence, by increasing M, the problem of long propagation delay can be overcome, and the efficiency remains limited by the link quality, i.e. by the BER.

IV. DISCUSSION OF RESULTS

Throughput efficiency as a function of packet size N_d is illustrated in Figs. 2 and 3 for the three S&W protocols using link parameters typical of several underwater channels. Fig.2 shows the efficiency for $P_e = 10^{-3}$. The basic S&W-1 protocol is represented in solid, while the S&W-2 and S&W-3 are represented in dashed and dotted lines, respectively. The performance of each protocol is shown for several values of the range-rate product, lR. (Note that the efficiency depends on this product through the factor μ (11) rather than on the individual values R and l.) Typical system parameters that are of interest to the present project are low/high transmission rates R on the order of 100 bps and 1 kbps, and the link distances l between about 500 m and 5 km. Consequently, three representative values of the range-rate product were chosen: $5 \cdot 10^4$, $5 \cdot 10^5$, and $5 \cdot 10^6$ meter-bits/second (m-bps). The other parameters of the system are selected as N_{oh}=8, $T_{sync} = 16T$, and $M = 16$.

Let us focus on the S&W-1 protocol first. Obviously, its usefulness is limited to situations with a low range-rate product. At higher values of the range-rate product, the S&W-1 efficiency drops to an unacceptably low level, making the effective bit rate $R_{eff} = \eta_1 R$ practically useless. Except at very low rate (<100 bps) and very short distance (<500 m) its throughput efficiency is limited. For example, at R=100 bps and L=500 m (uppermost slid curve) the efficiency does not exceed 55 %, while as the distance increases to 5 km, 25% is the maximum that can be expected. The optimal packet sizes needed to achieve these values are about 250 and 500 bits, respectively. Choosing much shorter or much longer packets will result in a serious further loss in performance. The efficiency of S&W-1 can be improved by using either S&W-2 or S&W-3. These protocols show substantial improvement for an optimally selected N_d. As expected, S&W-2 always outperforms S&W-3, and notably so for higher range-rate products. Similarly as the basic S&W-1, S&W-2 and S&W-3 exhibit high sensitivity to the choice of packet size.

Fig.3 shows the throughput efficiency in the same framework, but for $P_e = 10^{-4}$. We observe that the efficiency is now higher, while the same general conclusions about the relative protocol performances still hold. It is worth noting that although the efficiency varies considerably with the packet size for all protocols considered, its shape is relatively flat for some range of packet sizes in the vicinity of optimum. This range is wider for a better quality link (lower P_e).

The fact that there is a range of packet sizes for which near-optimal performance can be achieved is encouraging from the viewpoint of a practical implementation where only a few packet sizes could be available to accommodate varying link conditions (distance, error rate). We must also recall that the best efficiency is obtained when the time-out is set close to the round-trip time. In a mobile scenario, the distance between the transmitter and receiver changes, and so does the optimal time-out. If a fixed time-out is used, its value must be set in accordance with the maximal distance between vehicles to prevent occurrence of false time-outs. Using a greater-than-necessary time-out will cause additional loss in efficiency. If the round-trip time is estimated (which is easily performed and is also used to aid the navigation system in the present application) the time-out can be adjusted accordingly.

The optimal value of packet size is shown in Fig.4 as a function of the range-rate product for two values of the error rate, $P_e = 10^{-3}$ and $P_e = 10^{-4}$. Shown in this figure are the analytical results for S&W-1 and S&W-2. The optimal packet size for S&W-3 can be obtained numerically; its value is similar to that of S&W-2 (slightly greater) and is not shown. Instead, Fig.4 shows the optimal packet size for the limiting case of S&W-2 with $M \to \infty$, which represents an upper bound on the maximal throughput efficiency. Maximal throughput efficiency as a function of lR is shown in Fig.5. We note that for a given P_e, increasing the group size M reduces the sensitivity of performance to $N_{d,opt}$.

It is interesting to use the results of Fig.4 and 5 to assess the performance of a candidate acoustic modem. For example, if an acoustic modem transmits at 100 bps over a 5 km link, using fixed size packets of 256 bits, it can achieve close-to-optimal throughput performance at $P_e = 10^{-3}$ if transmissions are organized in groups of M=16 packets. The resulting efficiency is about 65%.

The optimal packet size and the corresponding maximal efficiency as functions of the error probability P_e are shown in Fig.6 and Fig.7. These results reveal high variation of the optimal packet size with BER. Notably, this is the case with S&W-1, the fact that motivated adaptive packet size adjustment for channels with highly time-varying BER, e.g., in [10]. (Note, however, that unlike for the radio channels, the underlying fading model is often not known for acoustic channels.) The use of S&W-2 improves performance and also reduces sensitivity of the optimal packet size to both the link distance and the BER. (With an increase in M, the sensitivity to link distance can be eliminated completely.) As far as the practical system design is considered, where various factors may dictate a fixed packet size, or selection from a few different sizes, we note that good performance can be achieved with a reasonably small group size, e.g., M=16 for the system parameters considered.

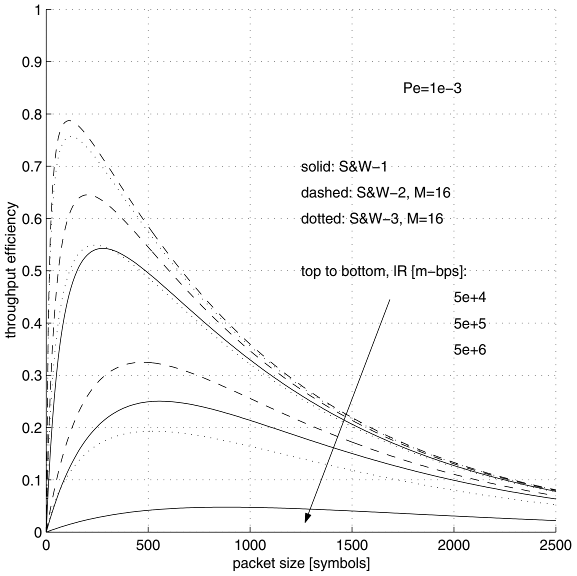

Fig. 2. Throughput efficiency η of S&W protocols as a function of packet size N_d for varying range-rate product lR. $P_e = 10^{-3}$.

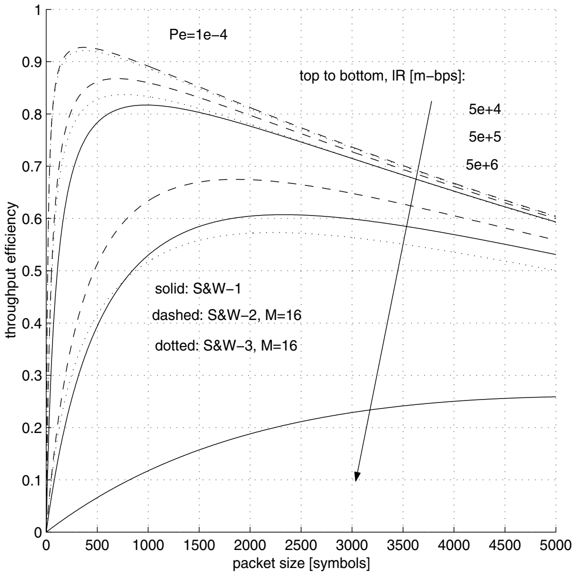

Fig. 3. Throughput efficiency η of S&W protocols as a function of packet size N_d for varying range-rate product lR. $P_e = 10^{-4}$.

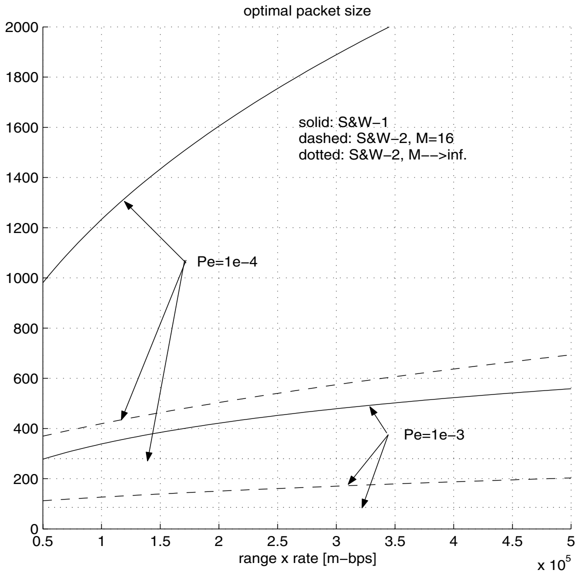

Fig. 4. Optimal packet $N_{d,opt}$ size as a function of range-rate product lR for $P_e = 10^{-3}$ and $P_e = 10^{-4}$.

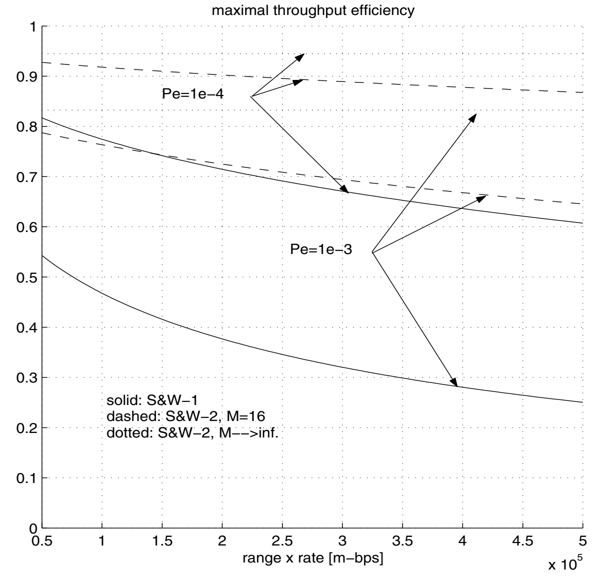

Fig. 5. Maximal throughput efficiency η_{max} as a function of range-rate product lR for $P_e = 10^{-3}$ and $P_e = 10^{-4}$.

V. CONCLUSIONS

Because the acoustic modems typically operate in half-duplex, selection of the ARQ scheme is limited to the Stop & Wait class of protocols. High latency of the acoustic channel renders the basic S&W protocol extremely inefficient, and limits is usefulness to systems that transmit at low bit rate over very short distances. For a multiple-vehicle search system that is of interest to the present project, this standard protocol is not a good choice. Instead, S&W schemes based on transmitting groups of packets for which selective acknowledgments are generated should be used. Throughput efficiency of these protocols can be maximized by selecting an optimal packet size as

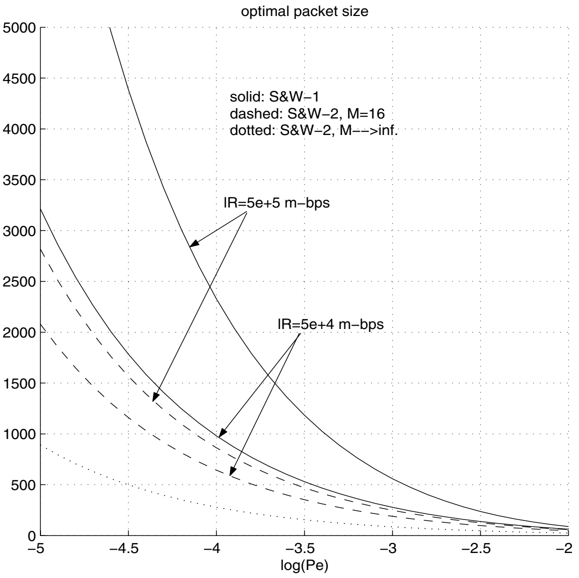

Fig. 6. Optimal packet size $N_{d,opt}$ as a function of bit error rate P_e for range-rate product $lR = 5 \cdot 10^4$ and $lR = 5 \cdot 10^5$.

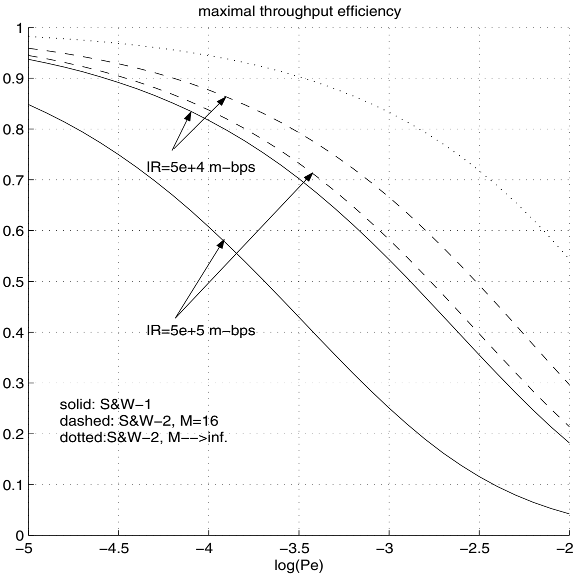

Fig. 7. Maximal throughput efficiency η_{max} as a function of bit error rate P_e for range-rate product $lR = 5 \cdot 10^4$ and $lR = 5 \cdot 10^5$.

a function of the acoustic link parameters (transmission rate, link distance, and error probability) and the group size (M). In addition to increasing the throughput efficiency, modified S&W protocols offer lower sensitivity of packet size selection to both the range-rate product and the error probability.

To fully utilize the limited resources of an acoustic channel, future system design should focus on implementing an adaptive ARQ scheme. Two aspects can be considered in doing so: (1) adaptive adjustment of the time-out in accordance with the measured instantaneous round-trip time, and (2) adaptive adjustment of the packet size in accordance with the measured instantaneous error probability and link delay.

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