Maximizing Channel Utilization for Underwater Acoustic Links

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***Abstract*—Underwater acoustic channels suffer from long delays and high bit error rates. In addition to these challenges, the unique bandwidth–distance relationship of underwater links makes straightforward application of traditional networking techniques suboptimal. This paper presents an analysis of the application of three techniques: forward error correction, packet size adaptation, and packet train size adaptation in terms of their effects on channel utilization in underwater acoustic environments. Our analysis provides insight that can guide the design of MAC and routing protocols. Results from simulations of the techniques in combination demonstrate how increases in channel utilization can be achieved in the face of underwater acoustic channel constraints.**

Technical Area:
10.1 Other [Underwater Acoustic Networks]

I. Introduction

A large number of applications for underwater sensor networks exist [1]; however, due to limitations of the acoustic channel, providing efficient communication is a challenging problem. Propagation delay, absorption loss, and low bandwidth are only some factors that must be taken into account in underwater acoustic links. Developing protocols that provide effective communication in terms of timeliness of data, reliability, and energy consumption must take into account these factors.

One metric for communication efficiency is channel utilization. In the face of limited bandwidth resources, protocols that require the channel to be either idle, or used sending data that is not useful to the receiving applications, have a large negative impact on the system. The long propagation delays in underwater networks cause acknowledgment-based reliability mechanisms to severely reduce the channel utilization, due to the need to wait for response from the receiver; however, the potentially high error rates of underwater channels [2] require some reliability mechanism to be built into the network stack to support applications with low tolerance for error.

Techniques to improve the channel utilization in the face of large propagation delays include using packet trains and forward error correction (*FEC*) schemes, but understanding the impact of the various parameters, such as packet size and the FEC strength, is an open problem. Additionally, properties unique to the underwater environment alter the conventional wisdom on how such techniques should be applied.

In terrestrial radio networks, as the distance between the sender and receiver increases, assuming the transmit power is held constant, the signal-to-noise ratio (SNR) at the receiver decreases. Lower SNRs can cause more bit errors at the receiver, depending on the channel encoding scheme used for transmission. Lower data rate schemes tend to tolerate lower SNRs while maintaining acceptably low bit error rates. For underwater acoustic links, in addition to this effect, the bandwidth available for transmitting the data also decreases with increasing distance [3]. The combination of these two effects has a large impact on the available data rates at given distances for underwater networks.

While previous work has attempted to minimize energy without considering channel utilization [4], [5], [6], to minimize delay [2], or to maximize channel utilization without considering the effects of the bandwidth–distance relationship [7], [8], none of this work achieves optimal channel utilization since each ignores a critical aspect of the underwater channel.

The main contribution of this work is an analysis of the effects of the bandwidth–distance relationship, high error rates, and long propagation delays on channel utilization. We demonstrate the effects of these properties on the use of forward error correction (FEC) and packet and packet train size adaptation.

FEC can be adapted according to the number of bit errors per block the code can correct. This optimal block code depends both on the error rate of the channel and the bit rate available. Optimal packet size depends on the bit error rate of the channel and the FEC code used. Packet training can be used to mitigate the effects of long delays on efficiency while extending the amount of time before an error is reported to the sender. By carefully analyzing the relationships between these three techniques and the effects of the underwater channel characteristics on their application, we demonstrate how to design protocols to maximize channel utilization.

The rest of this paper is as follows. Section II briefly describes related work in the area of efficient underwater communications. Section III presents the three adaptation mechanisms considered in this paper: forward error correction, packet size adaptation, and packet train length adaptation. Section IV presents the model of the underwater channel used in the paper and discusses how the bandwidth–distance relationship and long propagation delays affect channel utilization. Section V presents the results of our simulations. Finally, Section VI gives some conclusions and future directions.

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II. Related Work

Work in the design of underwater network protocols is relatively new. Park *et al.* develop a MAC layer protocol to attempt to deal with the long propagation delays [4]. This protocol sends synchronization messages containing a transmission time schedule for each node to attempt to avoid collisions and unnecessary delays. Harris *et al.* present a protocol to allow nodes to use a low-power wakeup mode to conserve energy when idle [5] and an analysis of the effect of the bandwidth–distance relationship on routing decisions based on hop length for energy-efficient routing [6]. However, none of these works consider channel utilization.

Heidemann *et al.* [2] provide a protocol to attempt to minimize delay in underwater acoustic networks. Pompili *et al.* [7] present a routing protocol that attempts to minimize energy and maximize channel utilization; however, this work does not consider the effect of the bandwidth–distance relationship and uses fixed packet train sizes.

Stojanovic [8] presents a packet train protocol to attempt to increase channel utilization without an analysis of the use of FEC or the specific effects of the bandwidth–distance relationship on the packet train sizes.

III. Mechanisms for Increasing Channel Utilization

We consider three interrelated mechanisms for increasing channel utilization in this work: FEC, packet size adaptation, and packet train size adaptation. In order to quantify the effects on network performance, a metric must be chosen. In this paper, we consider *channel utilization*, which is defined as the ratio of the amount of time the channel is transmitting useful data that is successfully received to the total amount of time the channel is used (which includes the time the sender is either idle waiting for acknowledgments or transmitting data that is not used by this receiver because it is either redundant or is received in error). We ignore protocol overhead for simplicity of notation; however, such overhead can be trivially included and has minimal impact on the results.

A. Forward Error Correction and Packet Size Adaptation

FEC is used primarily to avoid the need for retransmission due to bit errors in a packet and to reduce the amount of time it takes to recover losses due to such errors. Without any FEC, if a packet is received with bit errors, it is not useful to the receiver. Therefore, if the data is needed, a retransmission must be performed. The round-trip time (i.e., the time it takes from when a node starts sending data to when it ends receiving the corresponding acknowledgment) depends on the data rate of the channel, determined by the bandwidth and the modulation, on the packet length, and on the propagation and processing delays. If we let d be sum of the two-way propagation delay on the link, the processing time of the packet at the receiver, and the transmission time of the acknowledgment, the round-trip time can be computed as follows:

$$t_r = d + \frac{D}{R}, \quad (1)$$

where D is the number of bits transmitted before the sender stops and waits for an acknowledgment, and R is the data rate of the link. For high propagation delay links, such as those present in the underwater environment, the propagation delay is the dominant component. Therefore, some redundancy in the form of an FEC code can be added to each packet at little additional cost. Each FEC block code has the capability to correct a number of transmission errors. In this work, we consider Reed-Solomon codes [9], which map an information block consisting of k symbols of L bits each to a codeword of $n \geq k$ L-bit symbols (where typically $n = 2^L$), and which can correct up to $\frac{n-k}{2}$ symbol errors.[1] If the FEC block code is designed to correct more errors than actually occur, the extra redundancy added to the stream constitutes a waste and reduces the channel utilization. Therefore, the FEC should ideally be adapted based on the error rate of the channel.

The effect of FEC on channel utilization is dictated by the amount of redundancy added to each packet. Essentially, for each kL application data bits, there is an additional $(n-k)L$ bits of redundancy added. Therefore, the channel utilization in the absence of errors becomes:

$$\mu = \frac{kL/R}{nL/R + d}. \quad (2)$$

If the probability that the FEC cannot correct the bit errors in the packet is e_p, the channel utilization is as follows:

$$\mu = \frac{(1-e_p)kL/R}{nL/R + d}. \quad (3)$$

Note that e_p depends not only on the bit error rate, but also on n, k and L, which define the packet size and number of errors that can be corrected. The expressions in Equations (2) and (3) incorporate two mechanisms, namely, FEC and packet size adaptation. While it is certainly possible to use each of these techniques independently, their tight relationship makes it appropriate to treat them together.

Packet size adaptation has two primary effects. First, larger packet sizes send more data between acknowledgments, therefore reducing the fraction of time that the channel is unused. For an acknowledgment based protocol on a half duplex link, such as links in the underwater environment, if each packet is independently acknowledged, *i.e.*, there is no use of packet trains as described in the next subsection, the channel utilization is affected by increasing or decreasing n in Equation (2) with $n = k$. The channel utilization increases as n increases, assuming no errors on the channel.

In the face of errors, simply increasing the packet size may not in fact increase the channel utilization. Consider Equation (3) with $n = k$, *i.e.*, no error correction capability. Increasing n will lead to a corresponding increase in e_p (recall that e_p depends on the bit error rate and the packet size). Any packet containing an error will constitute wasted transmission time. Therefore, the increase in packet error rate will potentially offset the gains in channel utilization by

[1]For shortened codes, $n < 2^L$, but the correction capability is still $(n-k)/2$ symbols.

increasing the packet size. Therefore, the optimal packet size depends both on the round trip time and on the bit error rate of the link. Combining FEC with a larger packet size can potentially be used to increase the channel utilization beyond that if no FEC is used.

B. Packet Train Length Adaptation

Packet trains can be used to increase channel efficiency without increasing the probability of packet error. The technique involves sending a number of individual packets back to back before waiting for an acknowledgment. Selective or cumulative acknowledgments can then be used for each of the packet trains. We choose to use selective acknowledgments since they allow gap correction [10], leading to better channel utilization. The channel efficiency when using packet trains, with the probability of packet error e_p and packet train length T, is as follows:

$$\mu = \frac{(1-e_p)TkL/R}{TnL/R + d}. \tag{4}$$

Equation (4) shows that increases in T provide increased channel utilization. The cost of using longer packet trains is that the time it takes for the sender to learn about losses increases with the length of the packet train as follows:

$$t_r = d + \frac{TnL}{R}. \tag{5}$$

Therefore, the main drawback of using large packet trains is to delay the possible retransmissions. How much this cost matters depends greatly on the application. A soft real-time application may have timing dependencies that require the use of short packet trains, whereas bulk data applications, such as FTP, may be able to tolerate far longer delays.

C. Combined Effects on Channel Utilization

The combination of all three techniques allows a large adaptation space that can be used to increase the channel utilization depending on the link characteristics. Assuming a fixed data rate R, fixed propagation delay, and a fixed bit error rate, the effects of each of the three adaptation mechanisms can be explicated. From Equation (4) it can be seen that increasing the amount of data sent per packet, k, can increase the channel utilization; however, with an increase in packet size also comes an increase in packet error rate, e_p, which also depends on the relationship between n and k for the FEC block code used. Increasing the amount of redundancy per packet for the FEC, $n-k$, reduces the channel utilization in the face of no packet errors, but can lead to the ability to use larger packet sizes (allowing an increase in k) that might outweigh the reduction in utilization due to the redundancy added. Finally, increasing the packet train length, T, decreases the amount of time spent waiting for acknowledgments and so increases the channel utilization, with a cost of increased time before notification of a loss reaches the sender. The next section characterizes the effects of the underwater channel on the data rate and the propagation delay.

IV. Data Rate and Propagation Delay in Underwater Channels

Underwater acoustic channels differ from their terrestrial radio counterparts in a number of different ways. In this work we focus on the long propagation delays and the relationship between the distance between two nodes and the bandwidth available for use on the link to highlight how underwater channel characteristics affect channel utilization.

A. Propagation Delay

Underwater acoustic signals propagate at speeds depending on their depth in the water. This may lead to large differences in propagation speed even for equal distances, depending on the angle with respect to the z-axis of the transmission. The underwater propagation speed in m/s has been modeled accurately by Urick [11] as follows:

$$\begin{aligned} c &= 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 \\ &+(1.333 - 0.126t + 0.009t^2)(S-35) \\ &+16.3z + 0.18z^2, \end{aligned} \tag{6}$$

where t is one tenth of the temperature of the water in degrees Celsius, z is the depth in meters, and S is the salinity of the water.

The main factor that alters the speed of sound in water as depth changes is the temperature of the water. For oceans, this interval is between 2° C and 22° C. However, changes occur at different rates in three different regions, the region above the thermocline, the thermocline itself, and the region below the thermocline [12]. The salinity for oceans is in the interval $[32, 37]$ parts per thousand (ppt) with an average of 35 ppt [13].

Changes in the propagation delay affect d in Equation (3), with increasing delays reducing channel utilization. One important thing to note is that, unlike in terrestrial radio links, distance alone is not sufficient for determining delay times. It is possible in underwater links for a shorter link to have a longer delay.

B. Bandwidth–Distance Relationship

In underwater acoustic environments, the bandwidth available to a link depends on the distance between the sender and the receiver: as the distance decreases, the available bandwidth spectrum increases, allowing for a greater link capacity. For typical terrestrial radio environments, shorter transmission distances lead to either the ability to use lower power (due to less signal attenuation), or the ability to use higher bit rates (due to a higher signal-to-noise ratio), but the bandwidth available remains constant.

The frequency component of the channel is defined by the attenuation factor and the noise factor for the link. The SNR at a receiver distance ℓ from the transmitter can be modeled as follows [3]:

$$SNR(\ell, f) = \frac{P/A(\ell, f)}{N(f)\Delta f}, \tag{7}$$

where f is the frequency, P is the transmitted power, and Δf is the noise bandwidth at the receiver. The AN product, AN, determines the frequency-dependent part of the SNR. For each distance, there exists an optimal frequency for which the narrow-band SNR is maximum. Then, using this as the center frequency and following some definition of bandwidth (*e.g.*, 3 dB bandwidth), the maximum available bandwidth can be inferred.

The attenuation factor A depends on the absorption loss on the underwater link. Thorp's formula is used to express the absorption coefficient $a(f)$ as follows [14]:

$$\begin{aligned}10 \log a(f) = 0.11 \tfrac{f^2}{1+f^2} + 44 \tfrac{f^2}{4100+f} \\ +2.75 \cdot 10^{-4} f^2 + 0.003,\end{aligned} \quad (8)$$

where $a(f)$ is given in dB/km and f is in kHz. The absorption coefficient is the major factor that limits the maximum usable bandwidth at a given distance as it increases very rapidly with frequency.

Using this absorption coefficient, Urick models A in terms of the spreading loss and the spreading coefficient k for a distance ℓ and a frequency f as follows [11]:

$$10 \log A = k \cdot 10 \log \ell + \ell \cdot 10 \log a(f), \quad (9)$$

where the first term is the spreading loss and the second term is the absorption loss. The spreading coefficient defines the geometry of the propagation (*i.e.*, $k = 1$ is cylindrical, $k = 2$ is spherical, and $k = 1.5$ is practical spreading [11]).

The ambient noise in underwater environments is affected by four components: turbulence (N_t), shipping (N_s), waves (N_w), and thermal noise (N_{th}). The following formulae give the power spectral density of the four noise components in dB re μPa per Hz as a function of frequency in kHz [15]:

$$\begin{aligned}10 \log N_t(f) &= 17 - 30 \log f \\ 10 \log N_s(f) &= 40 + 20(s - 0.5) + 26 \log f \\ &\quad -60 \log(f + 0.03) \\ 10 \log N_w(f) &= 50 + 7.5 w^{1/2} + 20 \log f \\ &\quad -40 \log(f + 0.4) \\ 10 \log N_{th}(f) &= -15 + 20 \log f,\end{aligned} \quad (10)$$

and the overall noise power spectral density for a given frequency f is as follows:

$$N = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \quad (11)$$

The bandwidth, which depends strongly on distance in underwater acoustic links, affects the available data rate for the link, R in Equation (3). This has a major impact: increased R decreases the transmission times for both the useful data received successfully and for all data received in error and any redundancy sent.

Consider an example. As has been discussed, packet train length increases can mitigate the effects of propagation delay on channel utilization by increasing the number of packets transmitted back to back before waiting for an acknowledgment. Assume that there is some goal channel utilization to be achieved, and further assume that the bandwidth does not change with distance between nodes on the link. Then, as the distance between the sender and receiver is decreased, the propagation delay decreases according to Equation (6). This corresponds to a decrease in d in Equation (3) and an increase in channel utilization. Now, if the channel utilization was already at the target value, the packet train size, T, could be decreased. This may be desirable to decrease the amount of time before the sender is made aware of a loss. However, for the underwater acoustic links, decreasing the distance also increases the bandwidth. This increase corresponds to an increase in R in Equation (3), which *decreases* the channel utilization. When the distance between the sender and receiver shrinks, T can be decreased while still maintaining the same channel utilization. However, because the bandwidth increases, the amount that T can be decreased is less than if the bandwidth were to remain constant.

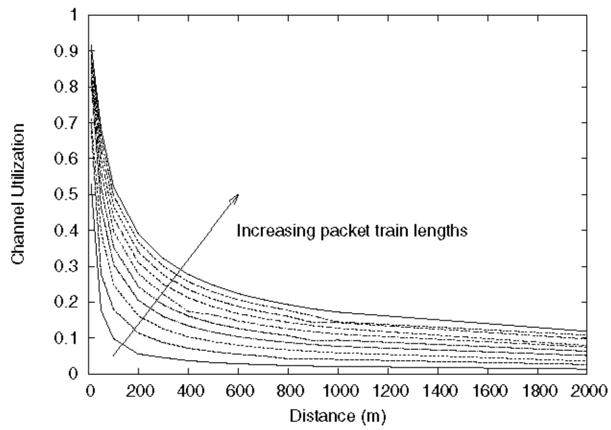

Fig. 1. Channel utilization: error rate 0, FEC level 0, packet size 48 bytes

V. Numerical Results

To demonstrate the effects of the bandwidth–distance relationship, the high bit error rates, and the long propagation delays on the use of FEC, packet size adaptation, and packet train length, we produced the models described in the previous sections in C++. We ran a large number of experiments varying the distance between sender and receiver from 10 m to 2 km and the bit error rate between 10^{-3} to 10^{-9}.

Variations in the parameters of the various adaptations were made as follows. The packet size was varied from 48 bytes to 1280 bytes. The FEC error correcting level ($(n - k)/2$) was varied from 0 to 2. Finally, the packet train length was varied from 1 to 10. In this paper, due to space constraints, we present a select number of results the demonstrate the trends, backing up the design intuitions in the rest of the paper.

To study the effects of packet train adaptation in isolation we present results from runs where the probability of bit error was zero and the packet size was 48 bytes. Additionally, no FEC was used (setting $k \equiv n$). The delay before the sender was notified of a loss grew from 0.03 s at 10 m to 2.73 s at 2 km for a train size of one. For a train size of 10, these delays grew to 0.17 s and 3.06 s respectively.

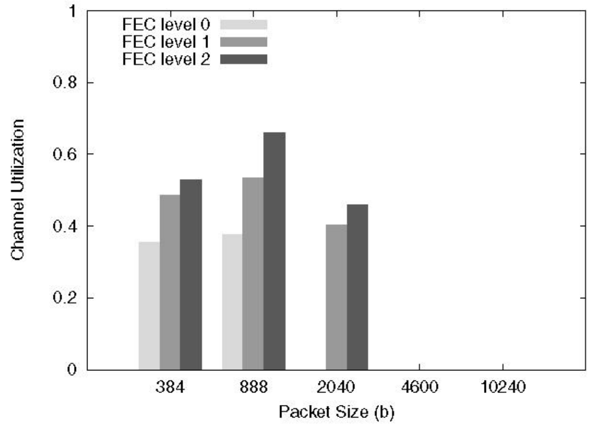

Fig. 2. Channel utilization: error rate 10^{-4}, distance 10 m

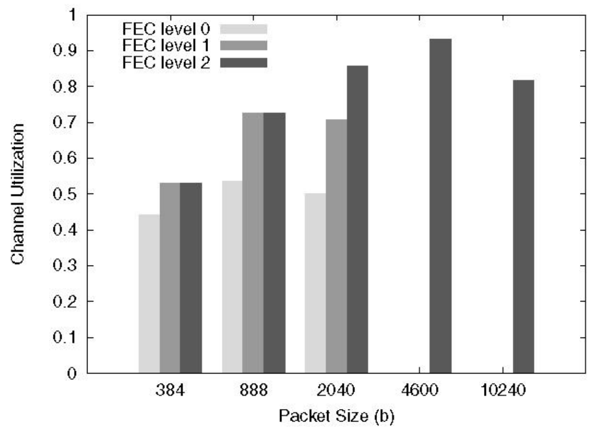

Fig. 3. Channel utilization: error rate 5×10^{-4}, distance 10 m

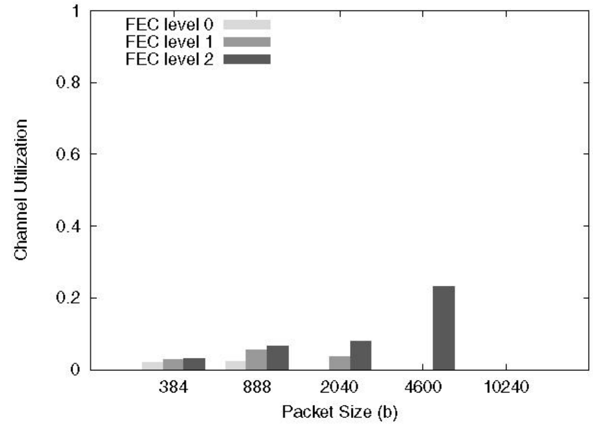

Fig. 4. Channel utilization: error rate 10^{-4}, distance 500 m

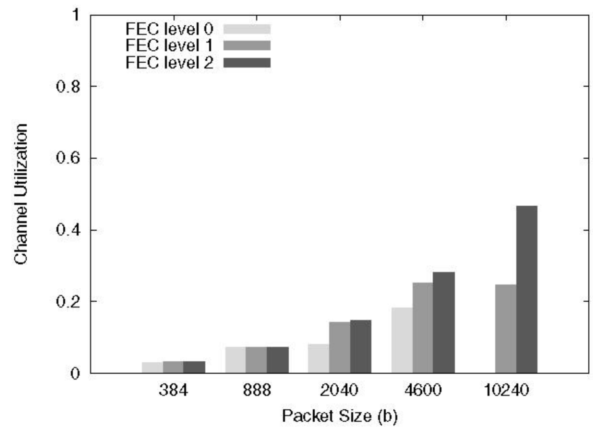

Fig. 5. Channel utilization: error rate 5×10^{-4}, distance 500 m

Figure 1 depicts the channel utilization as the distance between sender and receiver is increased along the z-axis (the receiver goes deeper into the water). The lines closer to the top of the graph (representing higher channel utilization) correspond to increasingly longer packet trains. Longer packet trains have significant effects for distances between 100 m and 600 m. At the edges of these bounds they tend to converge, because the delay is either short enough to not require the use of packet trains, or long enough to negate the effect of a train size change of only 10. Experiments run with longer packet trains at the larger distances achieved better channel utilization, but at a much higher cost in terms of the time before the sender was notified of a loss. As expected, as distances get shorter, the size of packet train needed to maintain a fixed channel utilization did not shrink rapidly due to the increase in bandwidth. We ran experiments where the bandwidth was held constant and found the optimal train length. We then used this train length in experiments where the bandwidth did increase with decreasing distance, as is the case in underwater channels. The resulting channel utilizations were as much as 16% lower than the optimal choice when the changing bandwidth was not taken into account.

Figures 2 and 3 depict the channel utilization for various packet sizes and FEC levels with error probabilities of 10^{-4} and 5×10^{-4} respectively and packet train lengths of 1. The distance between the sender and the receiver is 10 m along the z-axis. Two things to notice are that first, the longest packet size is not the optimal choice in either case. This is because the increase in the amount of data sent per packet does not outweigh the corresponding increase in packet error, e_p, even when FEC is used. Second, while in these results, adding the overhead for FEC capable of correcting 2 errors outweighs the cost of transmitting the extra redundancy, in other experiments, that extra redundancy did not always equal higher channel utilization.

Figures 4 and 5 depict the channel utilization for the same parameters as in Figures 2 and 3, but with the distance between sender and receiver increased to 500 m. The channel utilization is severely decreased due to the long propagation delays. Additionally, the bandwidth has decreased. These two effects change the optimal packet length from the shorter distance cases. Again, we performed experiments without changing the bandwidth as distance decreased, found the optimal parameters for all three mechanisms, and the used those parameters while taking into account the bandwidth–distance relationship and found the performance to be suboptimal.

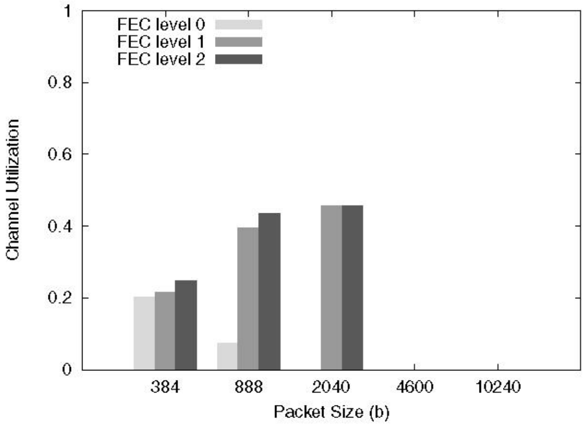

Fig. 6. Channel utilization: error rate 10^{-4}, distance 500 m, packet train 10

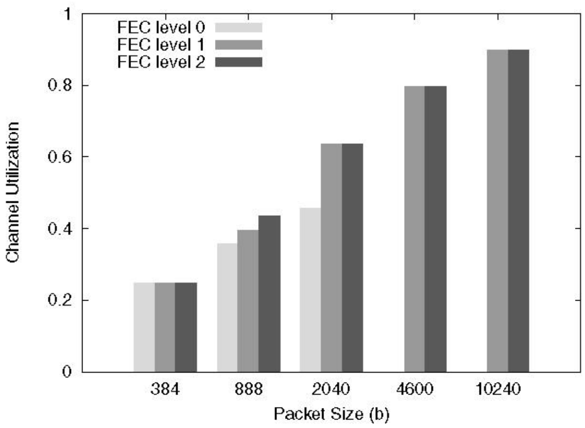

Fig. 7. Channel utilization: error rate 5×10^{-4}, distance 500 m, packet train 10

Finally, Figures 6 and 7 depict the channel utilization for the same parameters as in Figures 4 and 5, this time with a packet train length of 10. This increase in train length has a considerable effect on channel utilization but causes no change in the optimal packet length or FEC strength because changes in packet train length do not affect either the loss probability, bandwidth, or delay of the channel.

VI. Conclusion

This paper has presented an analysis of the effects of three techniques, namely, forward error correction, packet size adaptation, and packet train length adaptation, in underwater acoustic networks. This analysis and the simulation results that followed demonstrated how the combination of all three techniques can be used to mitigate the high error rate, long delay, and bandwidth–distance relationship of underwater channels to increase channel utilization.

Packet train length adaptation can be used to mitigate the effects of long delays without increasing the packet error probability. However, this mitigation comes at the cost of an increase in the amount of time that passes before the sender can be notified of a loss. Forward error correction and packet size adaptation can be used to mitigate both the propagation delay and high bit error rates. Our study demonstrated that the optimal choice of parameters for all three techniques depends on the distance between the sender and the receiver, which affects both the bandwidth available and the propagation delay for the underwater links.

Future directions for this work are to use these insights to design MAC and routing protocols to maximize channel utilization. Such protocols should also consider energy consumption and end-to-end delay to provide comprehensive support for a large number of applications.

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