A Cooperative ARQ Scheme in Underwater Acoustic Sensor Networks

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***Abstract* - We propose an efficient cooperative ARQ (Automatic Repeat reQuest) scheme for underwater acoustic communications, in which cooperative nodes are used to provide more reliable alternative paths for a specific source-to-destination connection. Based on the knowledge of inter-node distances, a cooperative region is defined to include all possible candidates for cooperative nodes from a given pair of source-destination nodes. When the destination node receives an erroneous packet, it asks for retransmission from a cooperative node, which is selected in a closest-one-first manner from the nodes in the cooperative region. The selection procedure continues until the retransmission is successful. In this paper, we evaluate the proposed scheme by comparing it with a conventional S&W ARQ in terms of throughput efficiency. Computer simulation results show that the proposed cooperative retransmission scheme can significantly improve the throughput by increasing the probability of successful retransmission.**

I. INTRODUCTION

Underwater acoustic sensor networks are gaining huge interest. There are a wide variety of applications envisioned for underwater sensor networks, such as environmental monitoring, resource investigation, disaster prevention, and so on. To implement these applications efficiently, it is important to understand the characteristics of underwater channels and to design feasible communication schemes. The most representative characteristic of an underwater channel is high path-loss of signal power. This path-loss becomes more severe as the carrier frequency of the signal increases. Thus, RF signals typically used in territorial communications are undesirable for underwater communication. Instead, acoustic communication has been developed for underwater communication [1].

However, underwater acoustic channels are likely to be deteriorated due to time varying multi-path propagations and Doppler spread. Accordingly, a high bit-error-rate (BER) and an unsteady propagation delay are unavoidable. To establish reliable communication under such poor channel conditions, an ARQ protocol that organizes the retransmission of erroneous packets is highly required.

There are various ARQ schemes, including the Stop and Wait (S&W) protocol, in which the sender has to wait for an acknowledgement of successful transmission of the previous packet from a receiver before transmitting the next packet. The S&W scheme has been intensively studied as a solution for underwater communication because current acoustic modems typically support only a half-duplex mode [2]. To improve the efficiency of the S&W ARQ protocol some schemes transmit a block of packets at the same time so that the time spent waiting for acknowledgment is reduced [3-6]. In addition, several algorithms that maximize the efficiency of an ARQ scheme in wireless senor networks by controlling the packet size according to the quality of the link have been proposed [7-9]. In a multi-hop channel, an opportunistic acknowledgement scheme has been proposed [10]. Recently, an efficient ARQ scheme that utilizes the characteristics of long propagation delay in acoustic channels has been proposed [11]. In this scheme, concurrent transmission between nodes is possible, and the backward overhearing is utilized as an ACK. However, the existing S&W ARQ cannot overcome high BER and long propagation delays. Hence, a new efficient ARQ scheme for underwater communications is required.

There is a growing interest in cooperative communication techniques that are capable of achieving diversity gain efficiently in wireless communication systems. A node can participate in cooperative communication by providing an alternative path, as an intermediate node, along a specific source-to-destination route.

In this paper, an efficient cooperative ARQ scheme in an underwater channel is proposed. For a given source-destination node pair, neighbor nodes form a cooperative node-set in which each node is either closer than the source-destination distance to the source or to the destination. In the order of distance from the destination node, the cooperative nodes are requested to retransmit the erroneous packet. This cooperative retransmission can significantly increase the probability of successful retransmission. Consequently, the throughput efficiency is substantially improved.

II. PROPOSED ARQ SCHEME

A. System Model

A single-hop network is considered, as shown in Fig. 1. Assuming that each node knows the inter-node distance for its neighbor nodes, a cooperative region is self-organized for a given source-destination pair. When the destination node receives an erroneous packet, it asks the cooperative nodes for retransmission in a one-by-one manner until the retransmission is successful. Nodes closest to the destination are recruited first.

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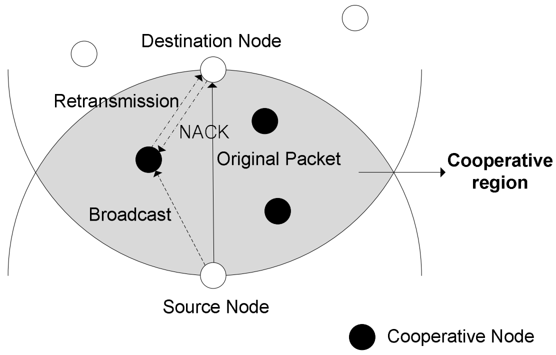


Fig. 1. A cooperative region for a single-hop network

In this paper, Rayleigh channel fading is considered. Thus, the average BER for BPSK modulation is represented by [12]

$$BER(SNR) = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{SNR}}{1+\overline{SNR}}}\right) \quad (1)$$

where SNR is the signal-to-noise ratio and $\overline{SNR} = 10^{SNR/10}$. The SNR of an emitted underwater signal can be expressed by the passive sonar equation [13]:

$$SNR = SL - TL - NL + DI \quad (2)$$

where SL is the source power level, TL is the transmission loss, NL is the noise power level and DI is the receiving directivity index in decibels. We consider the receivers as non-directional hydrophones, and thus, the receiving directivity index is zero.

Attenuation of an underwater acoustic communication channel that depends not only on the transmission distance l but also on the signal frequency f can be expressed as follows [14] :

$$A(l,f) = A_0 l^k a(f)^l \quad (3)$$

where A_0 is a unit-normalizing constant, k is the spreading factor, and $a(f)$ is the absorption coefficient.

The ambient noise in the ocean can be modeled using turbulence, shipping, waves and thermal noise. The overall power spectral density on the ambient noise is given by [14] :

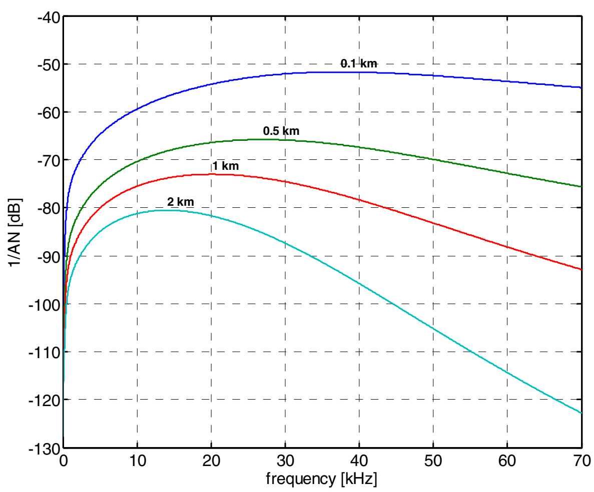


Fig. 2. AN product, $1/AN$, versus frequency

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (4)$$

In this paper, we adopted the method represented in [14], which determines the optimal frequency and corresponding 3 dB bandwidth. Using the attenuation $A(l,f)$ and the noise p.s.d. $N(f)$, the SNR can be evaluated. The average BER will depend on the SNR. Fig. 2 shows the $1/A(l,f)\ N(f)$, and an optimal frequency exists that maximizes the SNR for each transmission distance l. The optimal frequency and corresponding 3 dB bandwidth are shown in the Fig. 3.

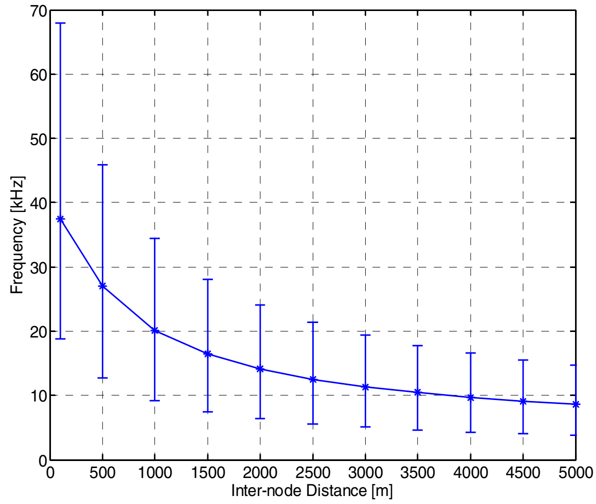


Fig. 3. Optimal frequency and corresponding 3 dB bandwidth

We assume that the source-destination node distance is 1 km, and thus, we can determine the operating frequency and corresponding 3 dB bandwidth as 20 kHz and 25 kHz, respectively. The average BER can be derived from (1) and (2). Fig. 4 shows the BER performance according to the inter-node distance when the operating frequency is 20 kHz and the bandwidth is 25 kHz.

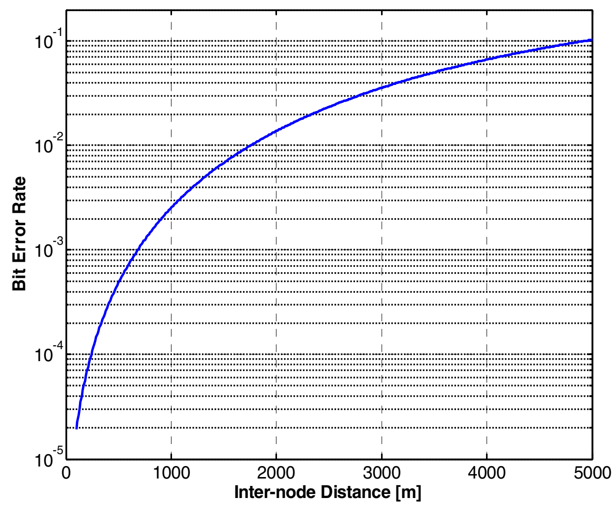


Fig. 4. BER versus inter-node distance

B. Operation of the Proposed ARQ Scheme

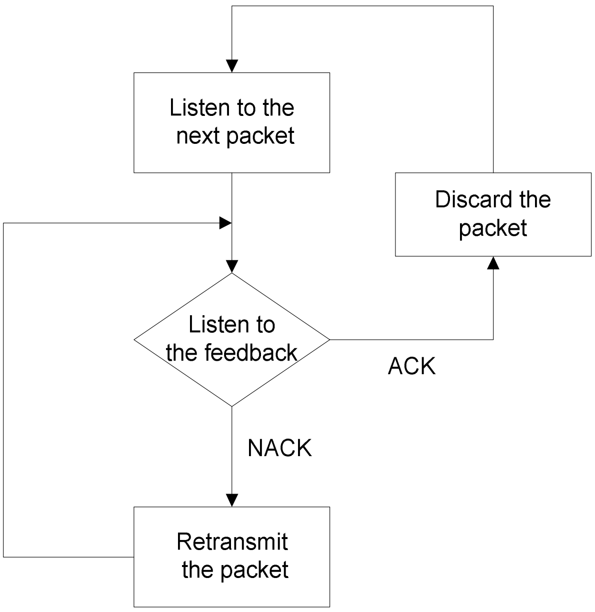


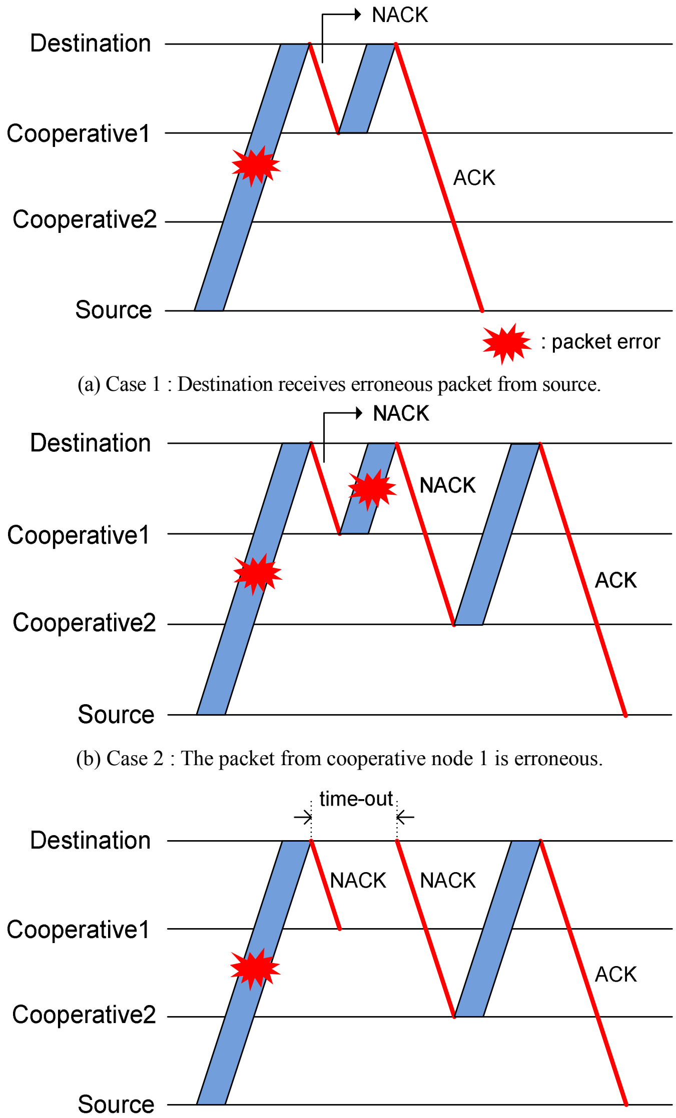
Fig. 5. Retransmission procedure in cooperative node

Fig. 5 shows a simplified procedure that a cooperative node follows in the proposed cooperative ARQ scheme. The cooperative node overhears the packets that the source node transmits toward the destination node. When no error is found, the destination node transmits an acknowledgement (ACK) packet toward the source node. The cooperative node overhears the ACK packet and recognizes that transmission was successful. Meanwhile, if an error is found, the destination node sends a negative acknowledgement (NACK) packet in such a way that only the closest cooperative node hears the NACK, and then the selected cooperative node retransmits a copy of the original packet to the destination node. If the retransmission fails again, the next closest cooperative node is asked to retransmit. Such a retransmission process continues until the retransmission is successful. In this scheme, the cooperative nodes temporarily store a copy of the original packet and discard the copy after overhearing the corresponding ACK packet.

If the cooperative node overheard an erroneous packet in the original transmission, it does not answer to the NACK packet from the destination node. The destination node waits for retransmission from the designated cooperative node until a predetermined time-limit has expired; this is referred to as time-out. If time-out occurs, the destination node requests a retransmission from the next closest cooperative node by transmitting the NACK packet. In the proposed scheme, the time-outs are determined differently depending on the distance between the destination node and the cooperative node. Unlike conventional retransmission schemes, where a destination node does not manage any time-out functions, a scheduling mechanism at the destination node using time-out is used.

C. Retransmission

In the proposed scheme, there are two types of time-out. First, if a source node does not receive an ACK or NACK within a predetermined time (the time-out of the source node), then it necessarily retransmits the original packet. Second, after transmitting the NACK packet to the closest cooperative node, the destination node waits for retransmission until a predetermined time-limit (the time-out of the destination node) has expired. If there are N cooperative nodes, the time-out of the source node (τ_{0S}) and destination node (τ_{0D}) are defined as follows:



(a) Case 1 : Destination receives erroneous packet from source.

(b) Case 2 : The packet from cooperative node 1 is erroneous.

(c) Case 3 : No data packet from cooperative node 1 is arrived.

Fig. 6. Retransmission cases

$$\tau_{0S} = 2t_p + 2\sum_{k=1}^{N} t_p(k) \tag{5}$$

$$\tau_{0D}(n) = 2\sum_{k=1}^{n} t_p(k) \tag{6}$$

where t_p is the propagation delay between the source and destination node, and $t_p(n)$ is the propagation delay between the destination and n-th closest cooperative node.

Fig. 6 shows three different cases for retransmission, where there are two cooperative nodes between the source and the destination node. In case 1, the destination node receives an erroneous packet from the source node. Next, the destination node transmits the NACK packet to cooperative node 1, which is the closest cooperative node to the destination node. Cooperative node 1 receives the NACK packet and retransmits the stored copy of the original packet. The destination node transmits an ACK packet to the source node if no error is found. At this time, the cooperative nodes that overhear the ACK packet discard their copy of the original packet. In case 2, the destination node receives an erroneous packet from cooperative node 1, as in case 1. The destination node then transmits the NACK packet to the next closest cooperative node (cooperative 2). In case 3, no data packet from cooperative node 1 arrives at the destination node within the time-out of the destination node. This is because the packet from the source to cooperative node 1 has an error, and thus, cooperative node 1 cannot respond to the NACK packet. After a time-out of the destination node, the destination node transmits a NACK packet to the next closest cooperative node.

III. SIMULATION RESULTS

In our computer simulation, a single-hop network with one pair of source-destination nodes was considered. The system parameters for the simulation are summarized in Table 1. As a performance measure, the throughput efficiency was obtained and compared with that of an existing S&W ARQ. The throughput efficiency was defined as the ratio of the time occupied by successful transmission to the total time occupied by both successful and re-transmissions. The optimal packet size and the optimal number of cooperative nodes to maximize the throughput efficiency were identified.

Table 1. System parameter values

Parameter	Value
Data rate	25 kbps
Carrier frequency	20 kHz
Source-Destination distance	1 km
Source power level	94 dB
Sound speed	1500 m/s

By varying the number of cooperative nodes, we observed the impact of the number of cooperative nodes on the throughput efficiency. Here, the packet size was assumed to be 500 bits. As shown in Fig. 7, when the number of the cooperative nodes increased, the throughput efficiency of the proposed scheme approached a saturation level. In addition, the number of cooperative nodes depended on the channel quality. Poorer channel quality necessitated more cooperative nodes to approach a similar saturation level.

In Fig. 8, we compare the proposed scheme with the S&W ARQ in terms of throughput efficiency for various packet sizes. To reduce the complexity of the simulation, we simulated the S&W ARQ and the proposed scheme with only

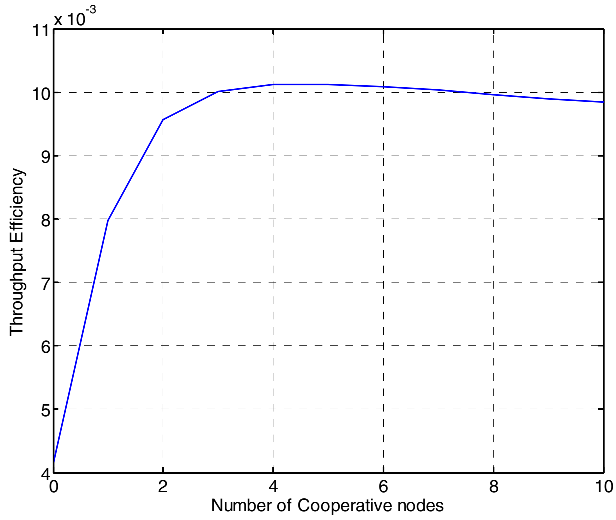


Fig. 7. Throughput efficiency versus the number of cooperative nodes

two cooperative nodes. The throughput efficiency of the proposed scheme outperformed the conventional S&W ARQ scheme. As expected, the throughput efficiency of 2 cooperative nodes (N_{CN} = 2) was much larger than that of 1 cooperative node (N_{CN} = 1). This is because the cooperative nodes provide alternative paths that are shorter than the direct source-destination path. This alternative path has a higher channel quality than that of the direct source-destination path. The throughput efficiency decreased as the packet size became larger. This is because the packet error probability is proportional to the packet size. For example, under the conditions of Table 1, the optimal packet size for the proposed scheme with 1 cooperative node is 500 bits.

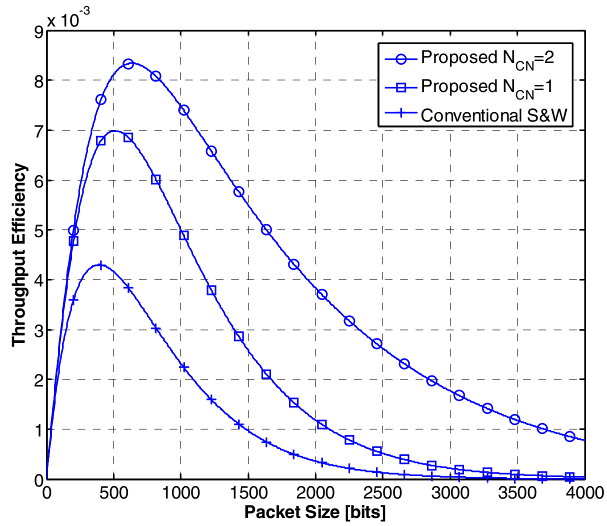


Fig. 8. Throughput efficiency versus packet size

IV. CONCLUSION

In this paper, an efficient cooperative ARQ scheme was proposed for underwater acoustic channels. This scheme uses cooperative nodes that provide alternative paths as intermediate nodes along a specific source-to-destination route. This alternative path has higher channel quality than that of the direct source-destination path. Through the computer simulation, we evaluated the proposed scheme by comparing it to a conventional S&W ARQ in terms of throughput efficiency. We demonstrated that the performance of the proposed scheme was substantially better than of the S&W ARQ scheme. This improvement is likely due to the cooperative nodes that provide an alternative path that increases the probability of successful retransmission.

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