Tier-Based Underwater Acoustic Routing for Applications with Reliability and Delay Constraints

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***Abstract*—UnderWater Acoustic Sensor Networks (UW-ASNs) are experiencing a rapid growth, due to their high relevance to commercial and military applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance. However, the design of efficient communication protocols for underwater sensor networks is still an open research problem because of the unique characteristics of the underwater acoustic communication channel such as limited bandwidth, high and variable propagation delays, and significant multipath and scattering.**

In this paper, we introduce a tier-based distributed routing algorithm. The objective of the proposed algorithm is to reduce the energy consumption through adequate selection of the next hop subject to requirements on the end-to-end packet error rate and delay. The protocol is based on lightweight message exchange, and the performance targets are achieved through the cooperation of transmitter and available next hops.

***Index Terms*—Underwater acoustic sensor networks, Routing algorithm, Cross-layer design.**

I. INTRODUCTION

In recent years, UnderWater Acoustic Sensor Networks [1] (UW-ASNs) have experienced a rapid growth, due to their high relevance to commercial and military applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance. However, currently available underwater acoustic technology supports only low-data-rate and delay-tolerant applications. State-of-the-art typical experimental point-to-point acoustic modems use signaling schemes that can achieve data rates lower than $20\,\mathrm{kbit/s}$ with a link distance of $1\mathrm{km}$, while commercially available modems provide even lower data rate waveforms [2][3].

In addition, the recent availability of inexpensive hardware such as CMOS cameras and microphones able to ubiquitously capture multimedia content from the environment is enabling so-called Wireless Multimedia Sensor Networks [4], i.e., wireless systems designed to retrieve video and audio streams, still images, and scalar sensor data from the environment. Similarly, multimedia underwater sensor networks would enable new applications for underwater multimedia surveillance, undersea explorations, video-assisted navigation and environmental monitoring. However, these applications require more flexible protocol design to accommodate heterogeneous traffic demands in terms of bandwidth, end-to-end packet error rate and delay. To support such traffic demands, in this paper we propose a new cross-layer routing protocol to flexibly reduce the energy consumption by selecting energy-efficient next hops subject to target packet error rate and delay bounds under the unique challenges posed by the underwater environment.

The drawbacks of existing terrestrial routing solutions for underwater networks [1] are well-understood. Therefore, in this article, we propose a tier-based routing protocol, where the network topology is partitioned into tiers, and each individual node, in determining a next hop towards a surface sink, is limited to selecting nodes that belong to its upper tier. In general, a tiered topology reduces the complexity of routing protocols, since, much like geographical routing, it provides each node with a set of coordinates that indicate a ”direction” towards the sink (physical coordinates in geographical routing, virtual coordinates in our proposed scheme). In addition to that, the virtual position can be used to estimate the end-to-end delay. To counter the effect of the carrier sensing delay caused by the high propagation delay, a Medium Access Control (MAC) protocol integrated with our proposed routing protocol is also introduced. The proposed low-complexity solution can be used to enable underwater monitoring applications with delay and reliability requirements.

The remainder of this paper is organized as follows. In Section II, we introduce the communication architecture for underwater sensor networks and the underwater propagation model. In Section III, we describe how to construct a tiered topology and a Medium Access Control (MAC) protocol to be integrated with our proposed routing protocol. In Section IV, we introduce the proposed routing protocol. In Section V, we assess the performance of the proposed solutions through simulation experiments. Finally, in Section VI, we draw the main conclusions.

II. PRELIMINARIES

In this section, we first introduce the communication architecture of three-dimensional underwater sensor networks. Then, we briefly describe the unique characteristics of underwater acoustic propagation.

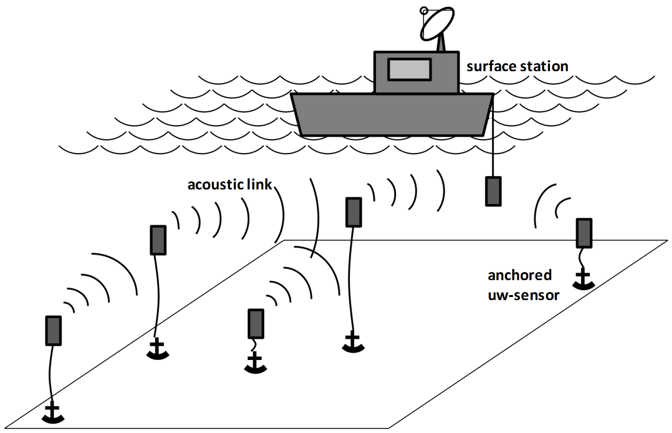

Fig. 1. The Architecture for 3D Underwater Sensor Networks.

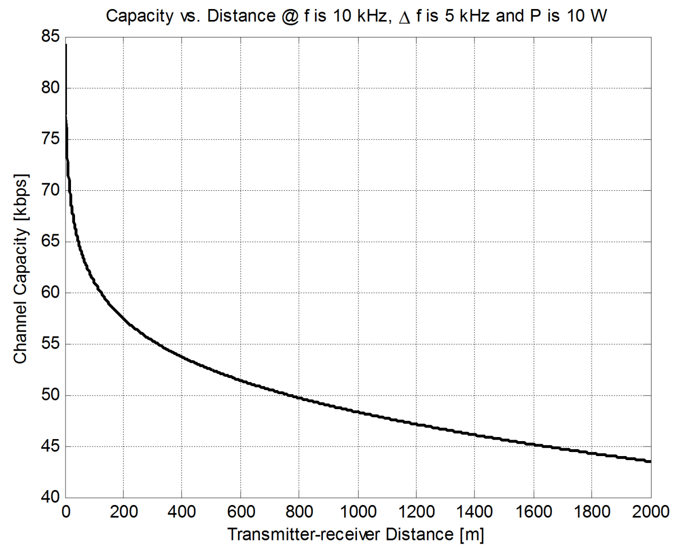

Fig. 2. The channel capacity with different transmitter-receiver distance when the carrier frequency is $10\,\text{kHz}$, the carrier bandwidth is $5\,\text{kHz}$ and the transmit power is $10\,\text{W}$.

A. Network Architecture

In three-dimensional underwater sensor networks, nodes are deployed at different depths to observe a given phenomenon and report to surface stations, as shown in Fig. 1. Each sensor is anchored to the bottom of the ocean and equipped with a floating buoy. The depth of each sensor can be regulated by adjusting the length of the wire that connects the sensor to the anchor. Underwater sensors are able to relay information to the surface station via multi-hop paths. Existing deployment strategies for underwater sensor networks, as discussed in [5], guarantee that the network topology be always connected. Therefore, we assume that at least one path from every sensor to the surface station always exists, and that higher sensor density increases the number of possible paths. Moreover, one or more surface stations are deployed on the surface of the ocean. Each surface station is equipped with an acoustic transceiver, and it may be able to handle multiple parallel communications with the underwater sensors and surface stations.

B. Underwater Propagation Model

Underwater acoustic propagation [6] is substantially different from its RF counterpart [7]. Specifically, underwater acoustic communications are mainly influenced by *transmission loss*, *multipath*, *Doppler spread*, and *high propagation delay*. The transmission loss $TL(d, f)\,[\text{dB}]$ that a narrow-band acoustic signal at frequency $f\,[\text{kHz}]$ experiences along a distance $d\,[\text{m}]$ can be described by the Urick model [6]:

$$TL(d, f) = \chi \cdot Log(d) + \alpha(f) \cdot d + A. \qquad (1)$$

In (1), the first term accounts for *geometric spreading*. The second term accounts for *medium absorption*, where $\alpha(f)\,[\text{dB/m}]$ represents an absorption coefficient. The last term, expressed by the quantity $A\,[\text{dB}]$, is the so-called *transmission anomaly*. More details can be found in [8].

III. Topology Control and MAC Protocol

As discussed above, since in underwater communications the transmission loss increases more than linearly with distance, relay transmission should be considered. Therefore, a well-designed topology control strategy can potentially reduce the end-to-end power consumption [9]. For this reason, we propose to partition the topology into tiers, and each individual node, in determining a next hop towards a surface sink, is limited to selecting nodes that belong to its upper tier. In general, a tiered topology reduces the complexity of implementing a routing protocol, since it provides each node with a set of coordinates that indicate a direction towards the sink (physical coordinates in geographical routing, virtual coordinates in our proposed scheme). In addition to that, the virtual position can be used to estimate the end-to-end delay. According to the tier where the node is located, a node can calculate the number of hops separating it from the destination.

We therefore hereby describe a procedure to be used at the surface station to construct a tiered topology, i.e., to select the radius of each tier. Based on the channel capacity expression between the transmitter and receiver, we introduce a procedure to partition nodes into different tiers starting from the surface station. In the routing procedure, a node is then limited to selecting nodes that belong to its upper tier to reduce the power consumption and guarantee the target end-to-end delay bounds. Then, a new MAC protocol integrated with our proposed routing protocol is introduced. The interaction between the MAC and routing protocols takes advantage of the tiered topology.

A. Topology Construction

The channel capacity can be expressed as

$$C(d) = \Delta f \cdot \log_2\left(1 + \frac{P \cdot TL^{-1}(d, f)}{\overline{N_0}}\right)\,[\text{kbit/s}], \qquad (2)$$

where $\Delta f\,[\text{kHz}]$ is the carrier bandwidth, $P\,[\text{W}]$ is the transmit power, and $\overline{N_0}\,[\text{W}]$ is the average ambient noise [10]. Figure 2 shows the channel capacity for a typical acoustic link with

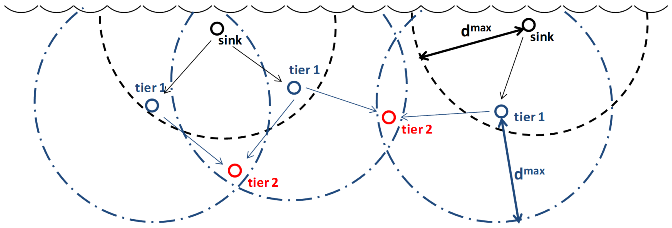

Fig. 3. Creating tiers from the sink.

varying transmitter-receiver distance. The carrier frequency f is set to $10\,\text{kHz}$, Δf is $5\,\text{kHz}$ and P is $10\,\text{W}$.

The channel capacity decreases with a higher transmitter-receiver distance and thus we can determine the transmission range (which determines the range of each "tier"), which we refer to as d^{max}, for a target channel capacity. For example, in Fig. 2, when the transmitter-receiver distance is $1000\,\text{m}$, the channel capacity is $48.32\,\text{kbit/s}$. Therefore, if the required channel capacity is $48.32\,\text{kbit/s}$, the transmitter-receiver distance cannot exceed $1000\,\text{m}$. In practice, the achievable data rate will be lower than the channel capacity because of the effect of interference.

Based on the target channel capacity, we can determine the value of d^{max} and accordingly partition nodes into tiers. The nodes in the range of the sink with radius d^{max} constitute the first tier. Nodes in the range of *at least 2* first tier nodes with radius d^{max} constitute the second tier, and so on. Note that this procedure guarantees the existence of at least two paths between the source and the destination, which guarantees a backup routing path in case of failures. We could increase 2 to more if necessary. The tier structure is illustrated in Fig. 3. With a tiered topology, the number of hops h between a source and destination depends only on what tier the source is located at.

B. Medium Access Control Protocol

To take advantage of the tiered topology, we propose a new Medium Access Control (MAC) protocol integrated with our proposed routing protocol as shown in Fig. 4. The transmitter at tier h transmits a Request to Send (RTS) packet, which includes the tier of the transmitter, to indicate that it has packets to send. Only idle nodes at tier $h-1$ will respond with a Clear to Send (CTS) packet, which includes the interference measured at the node and the average packet queueing delay. Since the propagation delay is high in underwater, we do not use carrier sensing and all idle $h-1$ tier nodes send a CTS immediately after receiving the RTS. Consequently, the transmitter will choose the node with minimum required transmit power as its next hop among those that satisfy the requirements on the end-to-end packet error rate and delay. The transmitter will announce the selected next hop by sending an Intent to Send (ITS) packet. After transmitting the ITS, the transmitter transmits the packet immediately. We consider a CDMA environment [11], where RTS, CTS and ITS are transmitted using a common spreading code which is known

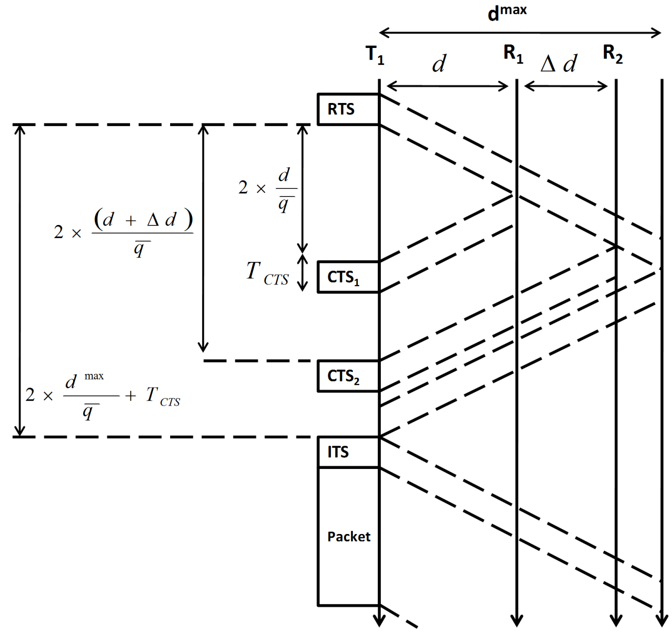

Fig. 4. The MAC protocol used to excute the proposed routing protocol.

by all nodes. The data packet is transmitted using a transmitter-assigned spreading code, where the parameters that will be used by the transmitter to generate the assigned spreading code for the data packet are included in the ITS.

A CTS may collide with another CTS. However, the probability of collision is small as illustrated in Fig. 4. In the figure, the distance between Node T_1 and Node R_1 is d, and the distance between Node T_1 and Node R_2 is $d+\Delta d$. Node T_1 will start receiving CTS_1 at $\frac{2\cdot d}{\bar{q}}$, and finish receiving CTS_1 at $\frac{2\cdot d}{\bar{q}}+T_{CTS}$. If Node T_1 starts receiving CTS_2 at $\frac{2\cdot(d+\Delta d)}{\bar{q}}$, a collision would happen when $\frac{2\cdot(d+\Delta d)}{\bar{q}} < \frac{2\cdot d}{\bar{q}} + T_{CTS}$, i.e., $\Delta d < \frac{T_{CTS}\cdot\bar{q}}{2}$. If T_{CTS} is $1\,\text{ms}$ and the sound velocity $\bar{q}$ is $1500\,\text{m/s}$, a collision happens only when Δd is smaller than $0.75\,\text{m}$. In fact, d^{max} in our simulation is $500\,\text{m}$, which is much larger than $0.75\,\text{m}$. Therefore, the collision probability for CTS packets is very small. The analysis above provides the rationale for not using a carrier sense mechanism in underwater and in general on propagation media affected by high propagation delay.

An RTS may also collide with an RTS from another transmitter. However, if the RTS collides at R_1 in Fig. 4, the probability that it also collides with the RTS at R_2 is very small. After R_2 receives the RTS, it will respond with a CTS. Therefore, T_1 can choose R_2 as its next hop, and the communication would not be interrupted.

IV. Routing Protocol

In this section, we introduce our end-to-end delay guaranteed distributed routing algorithm. In the problem formulation, a node i at tier h needs to transmit a packet m to a idle node j at tier $h-1$. P_i^{max} is the maximum transmit power dictated by hardware constraints at node i. The interference at node j, I_j, and the average queueing delay at node j, Q_j, are included in the CTSs from j. Moreover, E_{elec} is the distance-independent energy to transmit one bit, where we assume that the energy per bit needed by transmitter electronics and by receiver electronics is the same. The transmit power and the chip rate are P_{ij} [W] and r [chip/s], respectively. Therefore, the energy to transmit one bit from node i to node j is $2 \cdot E_{elec} + P_{ij} \cdot c / r$, where c [chip/bit] is the spreading code length.

The proposed algorithm allows each node to distributively select the optimal next hop and the optimal transmit power, with the objective of minimizing the energy consumption. Three constrains are included in the proposed algorithm to meet the delay-sensitive application requirements:

1) The transmit power should not exceed the maximum transmit power. Therefore, $P_{ij} \leq P_i^{max}$;
2) The end-to-end packet error rate should be lower than an application-dependent threshold PER_{e2e}^{max}. BER_{ij}, which represents the bit error rate on link (i, j), is a function of the transmission power and the interference at node j, $\Phi(P_{ij}, I_j)$. The packet error rate on link (i, j), $PER_{ij} = 1 - (1 - BER_{ij}^{L_D})$, where L_D [bit] is the packet size. Since the number of hops between node i and the destination is h, the end-to-end packet error rate is $1 - (1 - PER_{ij})^h$ and it should be lower than PER_{e2e}^{max}. Thus, $1 - (1 - PER_{ij})^h \leq PER_{e2e}^{max}$. Note that corrupted packets would be dropped. Therefore, the packet must be correctly forwarded from the source to node i. If the number of hops between the source and node i is h', $1 - 1^{h'} \cdot (1 - PER_{ij})^h$ should be lower than PER_{e2e}^{max};
3) The end-to-end packet delay should be lower than an application-dependent threshold T^{max}. We calculate $T_{MAC} = T_{RTS} + \frac{2 \cdot d^{max}}{\bar{q}} + T_{CTS} + T_{ITS}$ as the delay time between the beginning of RTS and the end of ITS, as shown in Fig. 4. Since node i does not have information about the upper tier nodes of node j, we derive the worst-case delay from node j to the destination as

$$T_{worst} = (h-1) \cdot (Q_j + T_{MAC} + \frac{L_D \cdot c}{r} + \frac{d^{max}}{\bar{q}}). \quad (3)$$

The distance between node j and the selected tier $h-2$ node is d^{max}, and we assume that upper tier nodes have the same queueing delay Q_j. Therefore, the number of hops between node j and destination is $h-1$, and the worst delay time would be $(h-1) \cdot (Q_j + T_{MAC} + \frac{L_D \cdot c}{r} + \frac{d^{max}}{\bar{q}})$. To guarantee that the end-to-end packet delay will not exceed the application-dependent delay bound,

$$T_{ITS} + \frac{L_D \cdot c}{r} + \frac{d_{ij}}{\bar{q}} + T_{worst} \leq T^{max} - (t_{i,now}^m - t_0^m), \quad (4)$$

where $t_{i,now}^m$ and t_0^m are the arrival time of packet m at node i and the time packet m was generated, respectively.

The proposed algorithm does not retransmit corrupted packets at the link layer. Besides, it time-stamps packets when they are generated by a source so that they can be discarded when they expire. Finally, note that the space of solutions to the above problem is for all practical purposes very limited and the problem can be solved by enumeration - no specialized solver is needed.

P: End-to-end Delay Guaranteed Routing

Given: $i, j, h, P_i^{max}, I_j, Q_j$

Find: j^*, P_{ij}^*

Minimize: $E_{ij} = 2 \cdot E_{elec} + \frac{P_{ij} \cdot c}{r}$

Subject to:

$$P_{ij} \leq P_i^{max}; \quad (5)$$

$$1 - (1 - PER_{ij})^h \leq PER_{e2e}^{max}; \quad (6)$$

$$T_{ITS} + \frac{L_D \cdot c}{r} + \frac{d_{ij}}{\bar{q}} + T_{worst} \leq T^{max} - (t_{i,now}^m - t_0^m). \quad (7)$$

V. Performance Evaluation

We have developed a discrete-event object-oriented packet-level simulator to assess the performance of the proposed cross-layer protocol. The physical-layer underwater acoustic link module models the underwater acoustic signal propagation channel with path loss, multipath, and underwater delays. The underwater acoustic link module generates bit error rate curves in terms of input parameters such as the link distance, the numbers of transmit/receive elements, total transmit power and acoustic noise level. We considered a CDMA environment, with fixed length spreading code length 7. The other simulation parameters are the same as described in [12].

We evaluate the performance of our proposed routing protocol in a three-dimensional shallow water environment. In addition, we compare it with the Greedy Routing Scheme (GRS) [13]. The GRS is based on geographical distance. We set the knowledge range [9] of GRS the same as the tier radius d^{max} of our proposed algorithm, and set d^{max} to 500 m. The 802.11 carrier sense multiple access with collision avoidance protocol (CSMA/CA) with RTS/CTS exchange is used with GRS. Note that our integrated MAC protocol does not employ carrier sense, and there is no collision avoidance mechanism. It reduces the end-to-end delay caused by the high carrier sensing delay in underwater since the slot time in the 802.11 backoff mechanism is set to 0.18 s and the contention windows CW_{min} and CW_{max} are set to 32 and 1024 [11]. Note that all figures are obtained by averaging over multiple topologies and report 95% confidence intervals. We set the chip rate r to 100 kcps, the spreading code length c to 7, the maximum transmission power P^{max} to 10 W, the data packet size to 250 Bytes, RTS, CTS, and ITS size to 10 Bytes. We do not consider or account for a physical-layer preamble in this paper. Still, we believe that the comparison among competing protocols is fair since all would equally need a preamble. In addition, we consider an initial node energy of 1000 J, a packet inter-arrival time of 5 s, a maximum number of retransmissions

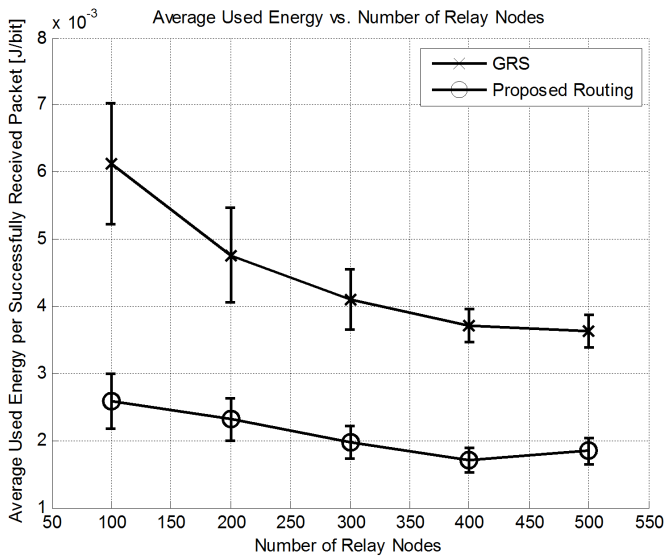

Fig. 5. Average Used Energy per Successfully Received Packet vs. Number of Relay Nodes.

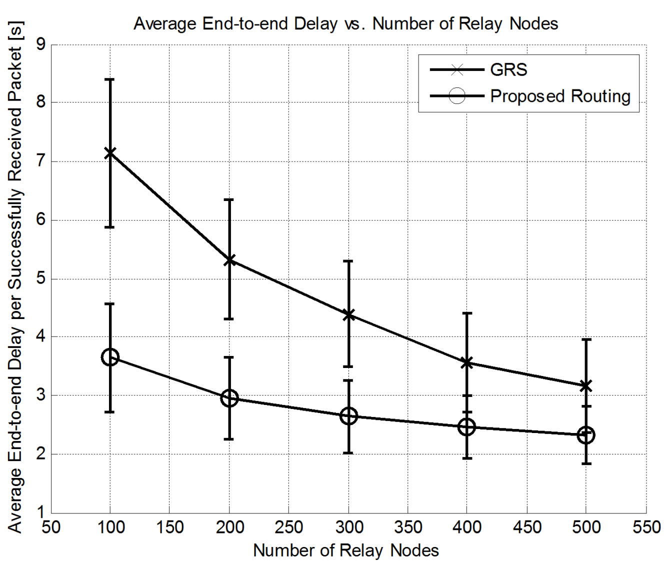

Fig. 6. Average End-to-end Delay per Successfully Received Packet vs. Number of Relay Nodes.

equal to 4, an end-to-end packet error rate threshold of 0.05, an end-to-end packet delay threshold of $8\,\mathrm{s}$, and a queue size of $10\,\mathrm{kBytes}$. All nodes are randomly deployed in a 3D shallow water scenario with volume of $1.5\mathrm{x}1.5\mathrm{x}1\,\mathrm{km}^3$. The number of source nodes is 50. Traffic packets are transmitted to any of the 4 surface stations.

In Fig. 5, our proposed routing algorithm is shown to considerably reduce the energy consumption by selecting suitable transmit power compared with GRS. Moreover, when the number of relay nodes increases, the number of upper tier nodes increases. Therefore, after the transmitter transmits an RTS, more idle upper tier nodes will respond with CTSs and consume more energy. However, the energy consumption

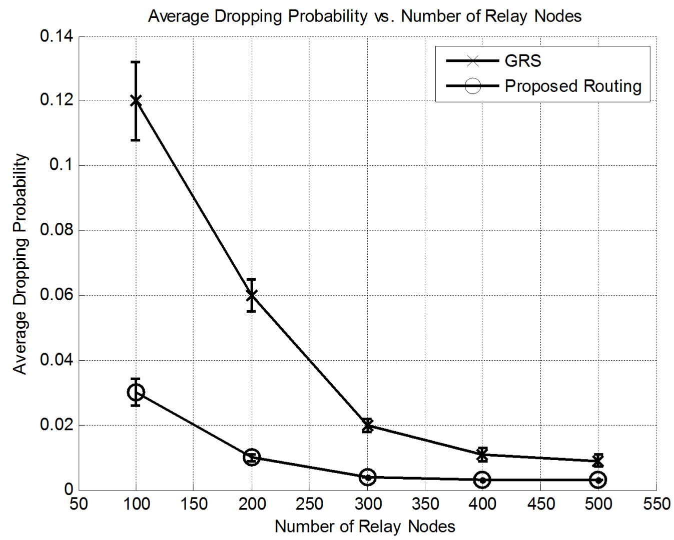

Fig. 7. Average Packet Dropping Probability vs. Number of Relay Nodes.

only increases when the number of relay nodes is large. Fig. 6 shows the average delay of successfully received packets. GRS does not select a backup routing path. Thus, if the next hop is busy, the transmitter must wait and transmit an RTS again. This also increases the packet dropping probability, as shown in Fig. 7. For example, when the number of relay nodes is 100, some source nodes may select the same relay node as their next hop. The packet delay time and the number of retransmissions increase. Our proposed routing protocol will select an optimal next hop from the idle upper tier nodes. Therefore, GRS has higher end-to-end delay time and packet dropping probability compared with our proposed algorithm.

VI. Conclusions

We proposed, discussed and analyzed a routing protocol for underwater acoustic sensor networks. Our proposed routing protocol adequately selects the next hop among idle upper tier nodes. The end-to-end delay is reduced by avoiding the high propagation delay caused by retransmissions. Moreover, in a cross-layer fashion, our proposed algorithm selects optimal transmit power through the cooperation of transmitter and receiver to achieve the desired level of reliability and data rate according to application needs and channel condition. Our proposed routing protocol was shown to consistently outperform GRS in terms of energy consumption, average end-to-end delay and packet dropping probability.

Acknowledgment

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