Short Paper: Token-based Data Collection Protocols for Multi-Hop Underwater Acoustic Sensor Networks

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ABSTRACT

We propose two novel token-based data collection protocols for multi-hop underwater acoustic sensor networks (UW-ASNs). The proposed protocols, namely the tree-based protocol and the ring-based protocol, use tokens to guarantee contention-free medium access for each transmission and reliable collection of data from each node. For the tree-based protocol, we propose a depth-first traversal of a Minimal Spanning Tree (MST) rooted at the sink node, providing a constant factor two approximation for the optimal total data collection delay. For the ring-based protocol, we formulate the problem as a Traveling Salesman Problem (TSP), and use the Christofides Heuristic algorithm to prove a constant factor 1.5 approximation to the optimal solution. We also argue that the tree-based protocol is more suitable for large-scale networks, and the ring-based protocol for small-scale networks.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Network Services, Reliable Transfer

General Terms

Algorithms, Design, Reliability

Keywords

Data Collecting Protocols, UW-ASNs, Token, MST, TSP

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1. INTRODUCTION

Underwater acoustic sensor networks (UW-ASNs) are versatile with applications in oceanographic data collection, pollution monitoring, offshore exploration and tactical surveillance [1]. As in the wireless ad hoc network, terminals in UW-ASNs are vulnerable to the hidden/exposed terminal problems that are intrinsic of ad hoc networks which communicate via a shared medium without centralized control. Moreover, underwater channel's very large and variable propagation delay results in the Spatio-Temporal uncertainty that brings about more collisions than in terrestrial networks [10]. Collisions make communication unreliable and retransmissions consume extra energy while increasing the delay. Consequently, design of a suitable data collecting protocol with high reliability and less access delay for this challenging environment is still an area worth investigating.

In this paper, we consider a multi-hop underwater network that is carefully deployed such that nodes are within the vicinity of the phenomenon of interests and the whole network is a connected graph. Different from the underwater networks in [1, 9], our system does not have dedicated gateway nodes that transfer data to user. Instead, all the sensor nodes have identical capacities for collecting and forwarding data, and the data are collected by a submarine or vessel (mobile collector) that passes by. As shown in Fig.1, for a specific round of data collecting, there is a unique node (sink node) acting as the gateway between the mobile collector and the rest of the network. This solution resolves the "energy hole problem" [4] that a regular sensor network suffers. Furthermore, to conserve energy, our data acquisition process is demand-driven, i.e., the sensors remain silent until they receive a direct or relayed request from the data collecting vessel. Prior work to resolve collision problems in UW-ASNs have been proposed [7, 3, 6, 10, 2, 8]. Basically, all the existing solutions can be divided to two categories, namely, the contention-free protocols (such as TDMA, FDMA) and the contention-based protocols (ALOHA, CSMA, and variants of them). Slotted Floor Acquisition Multiple Access (S-FAMA) proposed in [6] combines carrier sensing with a

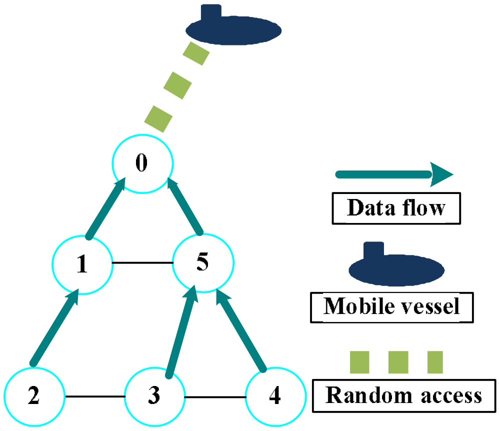

Figure 1: A multi-hop underwater acoustic network.

dialog between the source and the receiver prior to data transmission. Although time slotting eliminates the need for excessively long control packets thus reducing the overall energy consumption, due to huge propagation delay, the handshaking mechanism will introduce long delays leading to low system throughput. A different approach to channel access was proposed in [8]. This solution is strictly tied to a sleeping schedule, which is optimized for minimal energy consumption and does not consider bandwidth utilization or access delay as objectives. So for data collection, those contention-cased protocols either introduce too much overhead or are harder to implement while contention free protocols such as TDMA, and FDMA, are not suitable for underwater environment (see for example [1] for details).

The previous work mainly focuses on providing media access and routing separately. In this paper, we describe two novel token-based data collection protocols that consider media access control and routing jointly. This protocol not only guarantees contention-free access but also robust to channel delay's variability. The two protocols, namely, the tree-based protocol and the ring-based protocol, make use of a depth-first traversal of a minimal spanning tree starting at the sink and the Christofides Heuristic algorithm [5], respectively, to get constant factor approximations to the optimal solution.

2. BASIC ASSUMPTIONS AND THE NETWORK MODEL

To reduce the complexity, we assume that the underwater channel is ideal, i.e. the attenuation effects and packet loss due to channel fading is ignored, and all packet loss is due to packet collisions. Since the underwater communication range is subject to the depth, temperature, salinity, etc, and quite hard to predict, we make a safe assumption of strong interference that each node in the network is within the interference range of every other node. Considering that one node within the interference range of another node is not always in the communication range of that, our network is still a multi-hop underwater network. Consequently, it may be possible to allow multiple simultaneous transmissions; providing spatial reuse in such networks via multiple tokens is part of our future work and not considered to be within the scope of this study. Therefore at any given time, only one node is allowed to transmit[1] . Furthermore, considering that data collected in UW-ASNs is small (i.e. 100 bits) and the distance between nodes can be quite large (ranging from hundreds of meters to several kilometers) [1], the transmission delay, i.e., packet size divided by bandwidth (in the order of milliseconds) is at least three orders of magnitude smaller than the propagation delay, i.e., distance divided by the speed of underwater acoustic signal (on the order of seconds). Therefore, the transmission delay is neglected in the model and only the propagation delay is considered.

An UW-ASN can be abstracted as an edge weighted graph $G(V, E, W_e)$, where V is the set of vertices representing nodes in the network, E is the set of edges which exists only when the relevant nodes can communicate directly, and W_e is the propagation delay on the acoustic channel between nodes.

The basic principles of the token-based data collection protocol are simple and easy to implement. When a data collector accesses the UW-ASN, the node (sink) that detects the collector and agrees to its access through a dialogue generates a token and launches it to traverse the network. When a node possesses the token, it gets the permission for data transmission, either for transmitting its own data or helping other nodes relay data; it passes the token to another node according to a token passing sequence embedded in the token. This mechanism guarantees that the network is contention-free.

We define the interval between the time of the token launching and the time that all data reaches the sink node as a data collecting round, and the duration of the round is the data collecting delay, which, in our model, composes of the propagation delay for the token traversing the network and the propagation delay for all data to be transmitted to the sink in the multi-hop manner. Our goal is to minimize the delay. Two kinds of token-based protocols are defined in the following sections.

3. TOKEN-TREE-BASED PROTOCOL

According to the above analysis, in order to design an efficient token sequence to minimize the total delay, we design this tree-based protocol.

We firstly construct a Minimal Spanning Tree (MST) in G(V,E,we) with minimal sum of edge weights to help generate the token passing sequence. Then this token starts from the sink node and performs a depth-first traversal of MST.

In the tour, when the token traverses downstream in the MST and reaches a node, it is merely passed on along the depth-first traversal by the node immediately until it finally reaches the leaf node of the MST. When the token traverses upstream in MST, the node passes it on and appends the data after it. An example of a specific token and data traversal in a network is shown in Figure 2, where the topology of the MST is illustrated and Node A is the sink for the specific round of data collection. The arrows indicate the transmission of the token (T) and the data from sensor nodes (denoted by the node ID), and their timing sequences are also shown in the figure. As one may read from Figure 2, the token traverse the network by the depth-first traversal sequence, i.e., A to B to C to B to D to B and to A, and while

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[1] Providing spatial reuse in such networks via multiple tokens is part of our future work and not considered to be within the scope of this study.

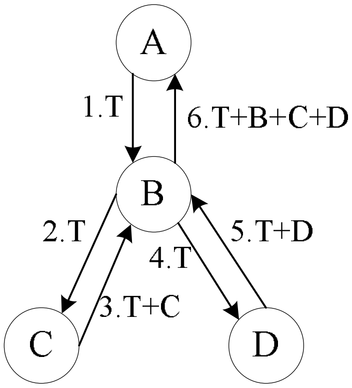


Figure 2: Tree-based data collection protocol

traveling downstream, the token travels alone, and while traveling upstream, it carries sensor data from leaf nodes to their parent nodes and eventually relay them to the sink node. In such a way, every node in the network will be visited in a data collection round, and no data will be trapped in an intermediate node at the end of the round.

We will show that the data collection delay incurred by the tree-based protocol is within a constant factor 2 of the minimum possible data collection delay.

Theorem: The delay cost incurred by the tree-based protocol is at most twice as much as that of the optimal algorithm.

Proof:

Assuming OPT is the optimal collecting scheme, and its delay is $COST(OPT)$.

The necessary condition that all data can be collected to the sink node is that every node transmits at least once. Given a weighted graph $G(V, E, W_e)$, one can formulate an MST in G with the minimal edge weight noted as $COST(MST)$. In the OPT solution, the minimum delay that must be incurred to collect the data items alone (ignoring any delays associated with the token) cannot be less than $COST(MST)$. Hence, $COST(OPT) > COST(MST)$.

In the tree-based protocol proposed above, every edge in the MST is traversed twice in one round of data collection, and the total delay incurred is thus$COST(TREE) = 2COST(MST)$.

Therefore, by combining the equations above, we can conclude that $COST(TREE) < 2COST(OPT)$.

We can also show in a specific example that the approximation factor of two is asymptotically tight. Assume a network is deployed in a ring topology as shown in Figure 3. In this network, the optimal solution is for the tokens and data to circulate along the ring, as shown in the Figure 3. So the optimal delay incurred is the sum of the propagation delay on every edge of the ring, namely,

$$COST(OPT) = \sum_{e \in ring} w_e$$

The tree-based protocol will construct an MST as shown in Figure 4, and the delay cost is twice MST which equals

$$2(COST(OPT) - \max_{e \in ring}(w_e))$$

As size of the ring goes to infinity, $max_{e \in ring}(w_e)$ in the equation becomes negligible, and the approximation factor goes to 2 asymptotically. From the example, we can see that in some topologies, the tree-based protocol may not perform well. For those cases, a ring-based protocol such as the one we present next might be preferable.

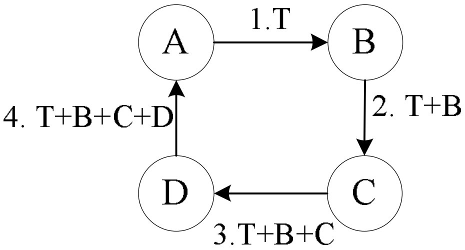


Figure 3: Optimal data collection flow

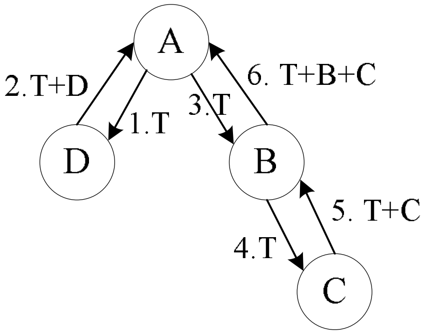


Figure 4: The tree-based data collection flow

4. TOKEN-RING-BASED PROTOCOL

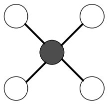
Different from the tree-based protocol, the ring-based protocol introduced in this section uses the cyclic token trace as the actual data trace. Upon forwarding the token to the next hop, a node appends its own data and relayed data to the end of the packet, until the token hits the sink node, when all data will be collected.

We formulate the optimization of the total delay as the Traveling Salesman Problem (TSP). An edge weighted graph $G(V, E, W_e)$ is considered. Assuming that the speed of sound is constant, the propagation delays between nodes are proportional to Euclidean distances. Therefore the edge weights we of the underlying network form a metric space (i.e., they are positive on all edges, symmetric, and satisfy the triangle inequality). It is known that the Christofides's Heuristic [5] is a polynomial-time algorithm that guarantees a constant factor 1.5 approximation for TSP on graphs with edge weights that satisfy the metric properties. The algorithm is described as follows.

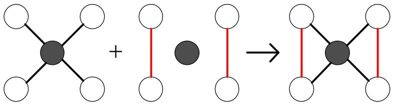
Step 1: Construct an MST in G, and some nodes have odd degrees, shown in Figure 5(a) as black dots.

Step 2:Find the minimum cost matching among nodes with odd degree. Adding matching edges makes the degree of all nodes even. This creates an Eulerian Graph shown in Fig. 4(b).

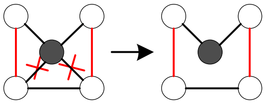
Step 3: Using triangle inequality (if any), apply shortcut to get TSP tour shown in Fig. 4(c).



(a) The minimal spanning tree



(b) Eulerian Graph



(c) TSP tour

Figure 5: Christofides's Heuristic Algorith

By using the Christofides's Heuristic, we can get a TSP tour that traverses all the edges of E exactly once.A unique problem in our protocol is that there may not exist a direct connection between two nodes to be added as the shortcut in step 3. If so, we can simply ignore the shortcut and stop the algorithm at Step 2. In this case the final solution we end up with may require the token to visit some edges more than once but this is not a fundamental constraint for our original problem. And the time to traverse two nodes involving two identical edges (i.e. one edge is from node i to node j, and the other is from node j to node i) can be considered equivalent to the delay incurred by a virtual short cut which still satisfies the triangle inequality (with equality). Therefore, this does not jeopardize the validity of the factor 1.5 approximation in [5].

A specific example of the data collection flow using this ring-based protocol is shown in Figure 6,assuming node 0 the sink node. When the token traverses this edge weighted graph $G(V, E, W_e)$along the tour generated by Christofides's Heuristic, at each transmitted node, the data and the token are merged and transmitted together.

Since the Christofides's Heuristic is a constant factor 1.5 approximation for metric TSP [5], the ring-based protocol offers better worst-case guarantees on the data collection delay than the tree-based protocol under the assumptions we listed in section 2.

In this paper, the transmission delay is neglected. But in large scale networks, the volume of the accumulated data could be very large, and consequently the transmission delay can be comparable to the propagation delay. The ring-based protocol will then incur greater total delay since particularly the nodes near the end have to transmit data from nearly the whole network, whereas the number of packets transmitted by any node in the tree-protocol is at most the size of the sub-tree rooted at it. With this consideration, the tree-based protocol may be better suited for large-scale networks, and the ring-based protocol for small-scale networks.

5. CONCLUSION AND FUTURE WORK

The token-based data collecting protocol provides contention-free medium access for the UW-ASN. The tree-based solution and ring-based solution create different mechanisms for the token to traverse the network and collect the data. They have been proven to be constant factor approximations to the optimal solution for minimum delay data collection in UW-ASNs.

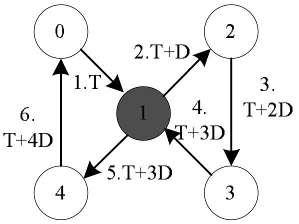


Figure 6: Ring-based protocol

Since only delay has been targeted in our design, future work will incorporate the energy consumption to address this problem and construct thorough simulations to compare the performance of our proposed protocols under different network topologies.

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