Abstract—In this paper we study non-geographical and mobile multi-hop ad hoc routing in a Underwater Sensor Network (UWSN), which is a novel network paradigm for ad hoc investigation of the world below the water surface using a wireless acoustic channel. However, the large propagation latency and very low bandwidth of the acoustic channel could potentially generate ubiquitous collisions and thus, any proactive protocol and flooding-based on-demand protocol is less efficient in this challenging new underwater environment. In this paper, we propose a multi-hop ad hoc routing and in-network processing protocol with no proactive routing message exchange and negligible amount of on-demand floods in the environment with homogeneous GPS-free nodes and random node mobility.

I. INTRODUCTION

The still largely unexplored vastness of the ocean, covering about two-third of the surface of earth, has fascinated humans for as long as we have records for. In this paper, we envision a large-scale underwater sensor network (UWSN) to explore the ocean and in particular, support solutions for the time-critical aquatic applications such as submarine tracking. To this end, a large amount of underwater sensor nodes can be air-dropped to the venue right after a recent submarine appearance. An area of hundreds of square nautical miles may need thousands of sensor units. At real time, each ad hoc sensor unit monitors local underwater activities and reports sensed data via multi-hop acoustic routes to a distant command center (i.e., the network sink). Clearly, the advantages of the novel UWSN paradigm are summarized as follows: 1) Localized and coordinated sensing is far more precise than the current remote telemetry technology, e.g., those relying on long-range directional frequency and ranging (DIFAR) sonobuoys; and 2) Scalability of UWSN ensures that a large area can be covered for time-critical applications with low-cost underwater sensor nodes.

However, the UWSN paradigm poses challenges compared to the existing wireless radio sensor networks. First, although a GPS-equivalence could be ported to a few nodes under water, there are no GPS-equivalent or precise positioning supports available for mobile underwater networks with more than hundreds of nodes. Second, since high-frequency signals are quickly absorbed in water, underwater networking must rely on low-frequency acoustic communications with the frequency upper bound reported as 1MHz at 60-meter range [2]. Third, the propagation delay in the underwater acoustic channel is five orders of magnitude lower than in the radio channel (1500 m/s). For instance, the propagation delay for traveling 1km is 0.67s. Consequently, such drastic reduction in communication resources makes the whole network vulnerable to packet collisions, which are mainly caused by the huge propagation delay. Therefore, proactively exchanging long or short routing messages under water inevitably leads to packet colliding disruptions even with very small transmission delay (\(\frac{\text{packet size}}{\text{link data rate}}\)). In addition, this implies that small route discovery flooding packets are vulnerable to colliding losses due to the very same reason. In a nutshell, conventional ad hoc and sensor routing protocols that heavily rely on proactive exchange or reactive flood are less efficient in underwater. However, in contrast to geographical routing algorithms recently proposed in [4], our scenario of a GPS-free on-demand ad hoc environment requires the use of flooding and thus poses great challenge to a multi-hop packet delivery service.

In this paper, we minimize the number of all packet transmissions to reduce the probability of collisions. This includes prohibiting proactive routing message exchange and minimize the total number of on-demand floods. These requirements are implemented in our proposed “Underwater Sensor Diffusion,” which is a multi-hop ad hoc routing and in-network processing protocol with no proactive routing message exchange and negligible amount of on-demand floods.

II. UNDERWATER SENSOR DIFFUSION

A. Design Assumption

Each UWSN node should be a low-cost embedded system equipped with necessary sensing devices. These nodes are able to communicate through a wireless acoustic channel. Here, we currently assume omni-directional acoustic transmission and reception. Since carrier sensing is not effective in underwater due to long propagation delay, we use pure ALOHA as an underlying MAC protocol. Due to water current and other underwater activities, underwater sensor nodes, except those nodes closely mounted on the sea floor, are randomly moving. From empirical observations, underwater objects may move at the speed of 2–3 knots, or 1.0–1.5 m/s, in a typical ocean current condition. We assume that network is dense enough such that there is no partition in the network and there is sufficient redundancy of paths between the sources and sink. This implies that in a network locality there are usually some redundant network members. In addition, an UWSN has at least one command center (sink) which disseminates commands to the network and meanwhile collects sensing data from the network. Except this imperative centralized control, the other components of the UWSN are tetherless and self-organizing.

B. Protocol Design

Our proposed protocol exploits in-network processing which aggregates homogeneous sensing reports originated from the same set of sources, thus mitigating channel contention. To further reduce the number of on-demand floods and to cope
with random node mobility, we use community-to-community forwarding [3], a dynamic unicast-based path management technique, to avoid packet floods (except one or two expensive but indispensable bootstrapping floods). In all cases, Underwater Sensor Diffusion seeks to avoid acoustic transmissions unless they are indispensable. Our protocol has 6 packet types: INTEREST, SINKDISCOVERY, UNICASTREPLY, PROBE, TAKEOVERHAPPENS and EVENTREPORT. Only the first two are flooding packets transmitted by MAC broadcast. The others are unicast packets with ACKs similar to 802.11. They are used in the following scenarios.

**Initial floods:** Initial floods are expensive and needed only at the beginning phase. Initially a sink (command center) floods an INTEREST message to the network. An INTEREST message contains monitoring information such as a monitored area, types of events, a report interval and expiration time. For example, given a task of monitoring a whale underwater, an example INTEREST command is as follows: type (whale), interval (5s), duration (15s), rect (0,0,100,100) and expire (17:90 July 6, 2005) [1]. After interest dissemination, when the interested event is detected at a node, it will issue a SINKDISCOVERY message (similar to RREQ message in an on-demand routing protocol) to find the optimal route towards the sink. The sink node will respond with a UNICASTREPLY toward the source.

In Underwater Sensor Diffusion, there are only two types of flooding messages: INTEREST and SINKDISCOVERY. An INTEREST is only sent once (as described below, changes made to the same interest are piggybacked into UNICASTREPLY message from the sink to the source). A source proactively sends a SINKDISCOVERY message when it detects an event. Then the sink reactively sends back a UNICASTREPLY. The efficiency of the proposed protocol rests on the fact that it limits the use of flooding unless it is necessary (the initial setup). This is achieved by virtue of the community-to-community forwarding approach.

**Community-to-community forwarding:** This forwarding approach exploits two innate characteristics of wireless sensor networks: redundancy of deployment and omni-directional signal propagation in wireless channels. The details of this design are available in our previous publications [3]. In a 3-D UWSN, the community area is defined by the intersection of three transmission balls of A, B and C. Those nodes who physically present in the community area are community members that can forward a packet between A and C. This approach can be extended to a chain of forwarding communities along a multi-hop path.

**Community configuration and re-configuration:** Communities are formed during the first UNICASTREPLY between a source and a sink. In practice, UNICASTREPLY packets are added with a 16-bit hop_count field. The field is reset to 0 at its originator, and is increased by 1 at each stop. Simply by passive and local monitoring, the community members set their community flags upon hearing three consecutive UNICASTREPLY packets of the same interest.

To cope with node mobility, we use proactive probing unicasts to reconfigure the dynamic communities. The source is responsible to send out a PROBE unicast every $T_{probe}$ interval. This is because the source knows whether there are further EVENTREPORTs. The sink responds with a UNICASTREPLY. If the current forwarder fails to forward a PROBE or UNICASTREPLY packet within $T_P$ time, then the current community members seek to take over the current forwarder. Here “take-over” means that a community member competes to forward the PROBE or UNICASTREPLY, with the sender’s MAC address set to the community member’s and receiver’s MAC address unchanged; thus, it tries to become the current forwarder. Since there are possibly multiple take-over contenders, a collision avoidance process is needed to decrease possible take-over collisions. The take-over trials use a collision avoidance time window at a proper level that is calculated according to the deployment settings. In this way, even though a take-over trial takes relatively long time (compared to radio networks), the trial succeeds with high probability. Once a unicast trial is ACKed by the next stop, all other competing trials stops after the competing senders hear the ACK. Then the unicast take-over trial successfully replaces the original forwarding. Whenever a take-over action succeeds, the taking-over node sends a short TAKEOVERHAPPENS to the source.

**In-network processing:** When a SINKDISCOVERY, PROBE or EVENTREPORT is forwarded towards the sink, it is often the case that other sensor nodes nearby the Center of Stimulus (CoS) of the event also detect the same interested event and try to send the same message to the sink. In our protocol, multiple SINKDISCOVERY or EVENTREPORT of the same interest are aggregated together if their timestamps are within a time threshold $t$ (which is proportional to the motion speed of the interested target). The aggregating node remembers the merged incoming links in its soft state. Then the later UNICASTREPLY from the sink on the reverse direction will be replicated to the previously merged links by the aggregating node. In addition, any PROBE message is aggregated into ongoing EVENTREPORT, and any TAKEOVERHAPPENS is aggregated into ongoing UNICASTREPLY whenever possible.

### III. Summary

We have designed and simulated a non-geographical and mobile multi-hop ad hoc routing algorithm for Underwater Sensor Network (UWSN) without GPS-equivalent supports (or without both precise and cost-efficient positioning supports). We have shown that flooding cannot be both reliable and efficient and thus, current GPS-free routing and diffusion schemes relying on (network-wise or controlled) floods, fails with high probability. From this, we have proposed community-based routing as the solution. Community-based routing has no proactive routing exchanges. It exploits unicast Probe flows and negligible amount of reactive floods to cope with node mobility and to minimize the number of reactive floods. Preliminary experimental results have confirmed the effectiveness and efficiency of the protocol.

### REFERENCES


