Multiple-UUV Approach for Enhancing Connectivity in Underwater Ad-hoc Sensor Networks

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Abstract - **Underwater sensor networks typically comprise of sensor nodes that are deployed in sufficiently large numbers for data collection, monitoring and surveillance. The acquired data is relayed by the sensors over multihop wireless acoustic communications links to sinks and collection points. While the sensors are generally static, the adverse channel and harsh environmental conditions increase the chances of link breakages due to fading and ambient noise. Our proposed scheme utilizes multiple underwater unmanned vehicles (UUVs, e.g. seabed crawlers) to enhance connectivity. The UUVs patrol the areas where connectivity is likely to be poor to overcome temporal interference and if necessary deploy more sensors to repair the breaks in connectivity. In the event that network becomes partitioned, the UUVs can also serve as local sinks to the sensors in the isolated partitions, and ferry the data from the isolated sensors to the nearest connected part of the network.**

I. INTRODUCTION

In wireless sensor networks, sensors are usually deployed in sufficiently large numbers for data collection, monitoring and surveillance purposes. The sensor nodes cooperate to relay the acquired data to sinks and collection points. Sensor nodes rely on portable and limited power supplies and therefore, the communications protocol must also be power efficient to achieve both robustness and scalability. The intermittent loss of connectivity due to node and/or link failure is inevitable, especially in underwater sensor networks, and this can adversely affect the performance of communications and related services that largely depends on the network connectivity, e.g., localization [7]. Poor connectivity can be due to sparse and non-uniform node distribution or temporal variations in channel leading to high bit error rates and intermittent connectivity even when nodes have not moved. Furthermore, shallow water is more susceptible to multipath and fading making it one of the most challenging environments for underwater acoustic communications [1].

While various techniques have been proposed for controlling groups of autonomous underwater vehicles and other instrument platforms used in underwater data collection and sampling applications [2], these methods cannot be applied to much smaller sensor nodes that are generally static. Extensive efforts have also been put into research on wireless ad hoc and sensor networks for terrestrial environments, but the RF-based technologies cannot be easily deployed underwater due to the unique characteristics of the underwater acoustic communication channel. Nevertheless, terrestrial networking techniques like clustering and spatial reuse of transmission resources have been adapted for use in underwater acoustic networks [3]. In this paper, a cooperative robotics approach is proposed to address the connectivity problem in underwater sensor networks. Our scheme relies on the sensor nodes being grouped into clusters after they are deployed [6]. We present the different methods for bridging temporal transmission interference, disconnections arising from changes in physical topology, and also suggest methods to maintain connectivity with isolated network partitions. We show the efficacy of this approach by simulation.

II. REFERENCE ARCHITECTURE

In this section, we describe the underwater sensor network architecture that is used as basis for our discussion. The network topology is itself an open research topic requiring much more investigation. For the purpose of illustration, we assume a two-dimensional underwater acoustic sensor network where sensor nodes are anchored to the seabed. Using acoustic links, the sensor nodes communicate with one another and cooperate to relay data over multihop routes to underwater collection points or sinks [4]. These sinks are connected via high-speed optical fibers to a monitoring centre on the shore. A typical region to be monitored is a warm shallow-water coastal area like the Straits of Singapore where there is heavy shipping and recreational traffic and the delicate natural ecological balance can be adversely affected by pollution and other foreign agents. In our study, we assume the region to be monitored has depth between 30 and 50 meters and an area of 2.5km×2.5km. Immediately after the nodes are deployed, they undergo an initial setup phase during which they organize themselves into clusters (Figure 1) and localize their positions with respect to the sinks[7].

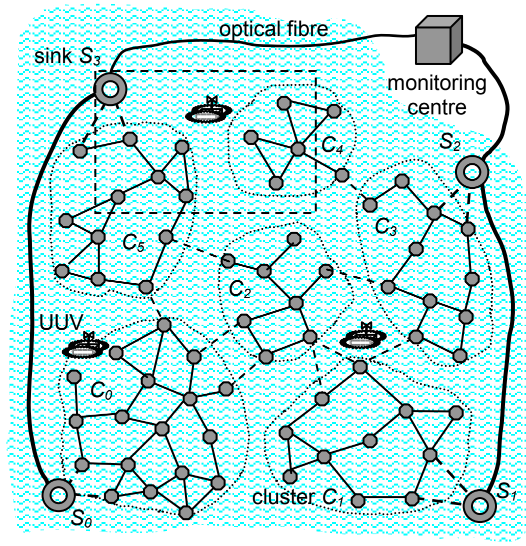

Figure 1: Underwater Sensor Network Architecture

The nodes use a simple ALOHA protocol [5] for medium access control to transmit periodic beacons for neighbor discovery and localization. As underwater sensor deployment is deemed to be sparse and the signal attenuates with distance, properly randomized transmission intervals can help to minimize collisions. The UUVs are equipped with more sophisticated transmission equipment, more resources like memory storage, and also carry a payload of sensor nodes (or communication relays) that can be deployed.

III. METHODOLOGY

The UUVs search for and identify critical communication gaps among the wireless sensor nodes, and then fill the gaps (acting as bridges) to enhance the connectivity of the network. These gaps may be temporal and once the channel conditions improve, they disappear, and the UUVs can move to other parts of the network. In cases where these are physical gaps due to poor initial deployment or sensors having been moved (e.g. by currents) or failed, UUVs can also be used to deploy replacements.

In adverse situations when the network becomes partitioned and connectivity cannot be restored by the use of UUVs as temporary bridges, we move UUVs to isolated partitions to act as local sinks or data aggregation points, so that sensor nodes in the isolated partition will continue to send their data to this UUV thinking that their data is routed to the global sink. Multiple UUVs can also be used to collect and ferry the aggregated data to parts of the network that is connected to the global sink where the data is unloaded, and forwarded as before [11]. Scheduling the deployment of UUVs depends on the ratio of the number of known partitions and roaming UUVs available.

A. Identifying Communication Gaps

During the setup phase, each sink broadcasts a localization message to identify itself. When a sensor node receives this message, it will note the hopcount value and rebroadcast the message after incrementing the value by one (hop). Every sensor keeps a record of its hopcount distances from all the sinks (initial values are set to a large number, e.g. 255, and consequently, a sensor that has no route to a particular sink will have 255 as the corresponding hopcount distance.) When a sensor node sends data to the sinks, it will attach the n-tuple corresponding to the hopcounts from the n sinks present (we use n=4.) The monitoring centre will use relevant algorithms to determine the actual physical location of the sensor (details of which are beyond the scope of this paper.)

As a UUV moves, it constantly listens for transmissions from the sensor nodes. A pair of nodes that are adjacent and within range of each other will have their n-tuple hopcounts differing by not more than one. E.g., in Figure 2, the n-tuple for node X is (10,10,10,3) indicating that it is respectively 10, 10, 10 and 3 hops from sinks S_0, S_1, S_2, and S_3, and for node Z, it is (9,9,9,3).

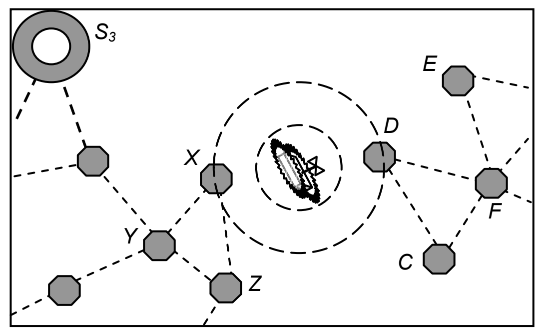

Figure 2: Identifying and Bridging Gap
(rectangular area at top left region of Figure 1)

When a UUV receives large differing n-tuple hopcounts, e.g. between node X and node D with (16,13,6,16), it identifies the area as a critical region. If the UUV is equipped with directional hydrophones and is able to estimate the signals' direction of arrival, it can perform a search using artificial potential field [8] control which simply maps the sensors as attractive force sources (where we equate a weaker signal to a stronger attractive force) and map other UUVs and obstacles as repulsive force sources; it then moves under the vector sum of the attractive and repulsive forces to a point that can ideally bridge the communication gap and link the two sensor nodes. Otherwise, it just roams around the area listening for the signals to get the "best" readings and tries to find a suitable point to bridge the gap.

The UUV serving as a relay then sends out a localization message containing its own n-tuple value (11,11,7,4) so that sensor nodes in the vicinity can update their n-tuple hopcounts. Each node will increment the message's values by one and compare with theirs, replacing their values with a smaller hopcount where applicable, e.g. new n-tuple values for nodes D and X would be (12,12,6,5) and (10,10,8,3) respectively. This localization message will continue to be propagated by a node after it updates the hopcounts in the message and its n-tuple hopcounts (with smaller values indicating that shorter paths to the sinks have emerged with the presence of the UUV); else, the node drops the message, e.g. node Z which does not need to update its n-tuple. If the link between nodes X and D had been temporarily disconnected and is subsequently restored, then the two nodes will be able to hear each other's transmissions again and update their *n*-tuples. This location is no longer a critical region and therefore does not require the presence of a UUV. When the UUV detects this situation, it can then move away.

Alternatively, if the UUV has remained in a critical region that is longer than a predefined duration[1], it assumes that the disconnection is permanent. It can then deploy a sensor (or relay node) from its carried payload to bridge the gap, and proceed on. If there is no available sensor to be deployed, then the situation will be communicated to the monitoring centre for a decision to remain as a bridge or move on (and let the link break again.)

B. Cooperative Search Algorithms

In this study, the searching of critical areas is a robot navigation problem that aims to provide full coverage of the whole area by cooperative robots. Although we do not assume the knowledge of the environment map and the ability to get exact location information, the robots have some intelligence to search for critical area cooperatively.

1) Advanced Potential Field based Search

Potential field based search is a simple searching strategy that can disperse the mobile robots in the environment with obstacle avoidance capabilities. We advance the traditional potential field based solution by adding the virtual repulsive force among the robots, i.e. UUVs, to make them move in different directions to effectively explore the whole network. As the UUVs move, they will broadcast their bearings. When a UUV receives this information, it will adjust its orientation accordingly to ensure that there is diversity in their bearings and therefore search for the critical gaps in different regions simultaneously. This search strategy does not require the use of any location information system, like Global Positioning System (GPS).

2) Predefined Search Patterns

Depending on the number of UUVs available for deployment and the estimated area to be monitored, various search patterns can be defined for each UUV before deployment. By designing a good search strategy, maximum coverage of the target area can be achieved by the UUVs (e.g. as shown in Figure 3.)

This can be more effective (as compared to the advanced potential field based search) in detecting critical gaps within the network, but gaps which are located further from the starting point of the search pattern may experience longer delays before they are detected and bridged. It should be noted that in our study, the predefined search strategy does not require the knowledge of the details in the environment (map) or the sensor/equipment to estimate the exact location of the UUV. We only assume that the UUV has the ability to detect its movement by odometry and compass therefore it can roughly estimate whether it has reached the predefined waypoints in the area.

[1] This duration depends on many factors, e.g. channel conditions, number of UUVs available, etc., and is likely to be an operational issue. There is however the opportunity to study this as an optimization problem with respect to the available resources and environmental conditions.

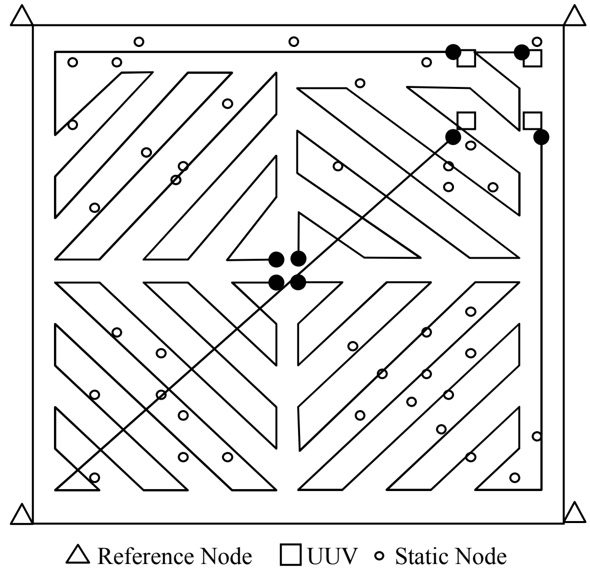

Figure 3: Predefined search pattern

3) Intelligent Perimeter Search

The clustering of sensors can be done using any of the known methods (e.g. [6]) to maximize connectivity within the cluster. This suggests that inter-cluster regions are where connectivity is more likely to break and it would be better to make the UUVs patrol these areas. This search method requires some additional capability on the UUVs to help them identify the inter-cluster areas dynamically, namely, ability to estimate the signals' direction of arrival using directional hydrophones, e.g., with 6 sectors (Figure 4.)

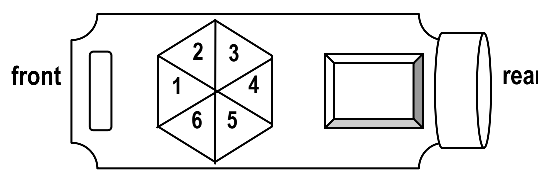

Figure 4: UUV with Directional Hydrophones

When sensors transmit, they identify themselves with their cluster identifier in the messages they send. A UUV traveling along the edge of the network along the fibre from sink S_2 to S_1 (cf: Figure 1) will first be able to receive signals from sensors in cluster C_3 on hydrophone sectors 2 and 3. As it approaches C_1 the hydrophone will receive signals from sensors in that cluster on sector 1 and possibly sector 2. The UUV will then make use of this information to move along the perimeter of each cluster to detect inter-cluster gaps before moving on to the next cluster.

To enhance cooperation among UUVs, each broadcasts the information of search status, e.g., the cluster being searched and/or has been searched recently, so that the UUVs can choose different clusters to search. Such cooperation relies on inter-UUV communications which may also need the (static) sensor nodes to help relay messages between UUVs that are not within range of one another.

IV. PERFORMANCE EVALUATION

We study the proposed schemes using simulation and analyze the performance of the system using the following metrics:

Connectivity – number of nodes connected to at least one sink. With higher connectivity, more nodes are able to forward collected data to the sink(s) for the purpose of data aggregation and/or analysis.

Average hop count – average hop count of each node to a sink. A lower hop count improves the delay involved in sending data to the sink(s) and the monitoring centre. This value is especially crucial if the application involves real-time monitoring and/or surveillance, where prompt action has to be undertaken for a particular event that is detected.

***k*-connectivity** – average number of sinks that nodes are connected to, where $0 \leq k \leq n$ (n=4 is used in our studies). Localization, which provides an estimate of each sensor node's location via its n-tuple hopcount from the n sinks, is only possible when each node has connectivity to at least k=3 sinks (for 2D triangulation.) It is therefore important to achieve a network with high k-connectivity so that location estimation can be performed.

A. Simulation Environment & Scenarios

In order to realize the simulation, some preliminary effort was required to integrate two different simulators: QualNet [9] for node communication and Player/Stage [10] for multi-robot collaboration and control of the UUVs. Using semaphores and shared memory between the two simulators, time synchronization and event signaling was achieved between them.

A total of 80 static nodes are randomly deployed in the 2.5km×2.5km area to be monitored during the initialization phase, with a reference node at each corner. We assume that the total payload of sensors carried by all the UUVs is 20 sensor nodes (i.e., the maximum number of additional sensors that can be dropped by the UUVs is 20).

Both the sensors and UUVs have a transmission range of about 250m. A simple, modified version of the ALOHA protocol with randomized transmission intervals and no retransmissions is used. Each static sensor node periodically broadcasts its hopcount information. Newly deployed sensor nodes and disconnected sensor nodes request for hopcount updates from their neighbours which will send their hopcount information immediately.

We consider the following two scenarios and compared the performance of the 80-node system with varying search strategies against the base case where 100 static nodes are initially deployed in a random manner:

Node failure (which could be due to corrosion, energy depletion, etc), whereby network partitions may be formed; and

Intermittent link failure which is a common phenomenon in underwater environments, especially shallow water whereby there is impulsive ambient noise.

B. Node Failure

Figure 5 to Figure 7 show the performance of the network with respect to time in the presence of node failures. When nodes fail, communication gaps may appear in the network. In the static case, a total of 100 nodes (i.e., with redundancy) are dropped initially in contrast to just 80 initial nodes. We can see that with the aid of multi-UUV collaboration, the network connectivity is enhanced by additional nodes dropped by the UUVs to bridge critical gaps, whereas if the nodes are randomly deployed from start, they may not be dropped at critical regions and hence do not serve to improve the network connectivity.

The perimeter search does not perform as well as the advanced potential field based and predefined searches because communication gaps may appear in the network at places other than inter-cluster areas. The predefined search is able to provide near full-coverage of the entire network and detect most of the gaps, while the intelligence component of our advanced potential field based search algorithm also helps to provide better coverage of the network. Similar improvements are also observed using one UUV.

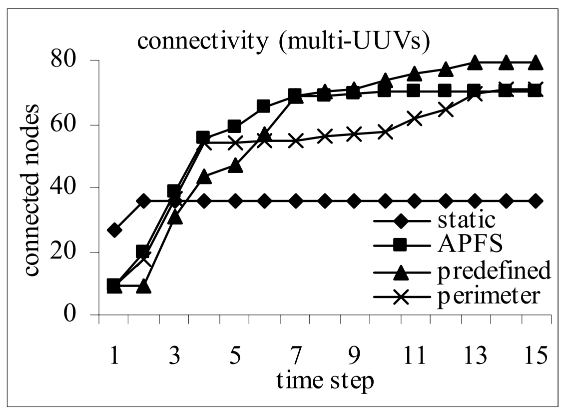

Figure 5: Connectivity during node failure

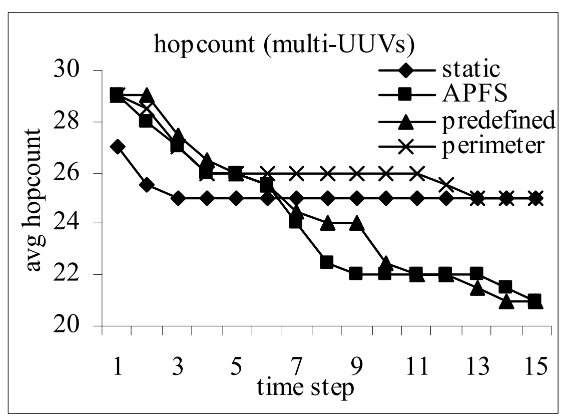

Figure 6: Hopcount during node failure

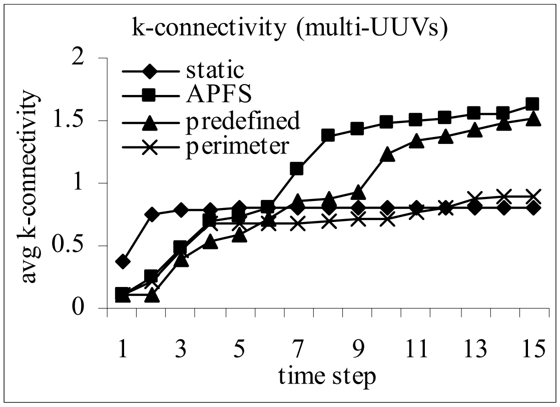

Figure 7: *k*-connectivity during node failure

C. Intermittent Link Failure

During intermittent link failure, communication between node pairs may be unpredictable and unreliable. Ambient noise often causes high bit error rates (BER) and low signal to interference noise ratio (SINR), and consequently, high packet loss.

Figure 8 to Figure 10 show the network performance during link failures, whereby channel quality is poor and sensor nodes may lose communication for short periods of time. During the first part of the simulations, our multi-UUV search approaches do not outperform that of the static case due to the difference in number of sensors used for communication during initialization.

As time progresses, the UUVs are able to detect regions with poor connectivity and critical gaps and they can either drop additional sensor nodes (up to a total of 20) or act as temporary bridges themselves. This helps to improve the connectivity of the network, as shown in the figures.

V. CONCLUSIONS

The harsh environment and adverse underwater communications channel poses many challenges to the deployment of sensor networks. The poor channel conditions can further deteriorate due to severe multipath fading in shallow water and high ambient noise. In this paper, we have proposed the use of multiple UUVs together with collaborative search strategies and simple schemes to identify communication impairments in underwater sensor networks. Methods to alleviate the communication degradation are proposed and validated using simulations focusing on the common causes of underwater communications problems, viz. node failure and intermittent link failure.

The results have shown that there is great potential in further improving the performance of underwater sensor networks, e.g. cooperation between mobile and static nodes for localization and networking, as well as, efficient use of UUVs as message ferries to bridge regions that experience severe communication impairments.

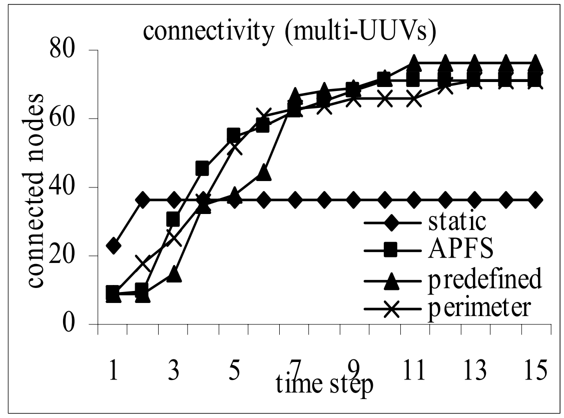

Figure 8: Connectivity during link failure

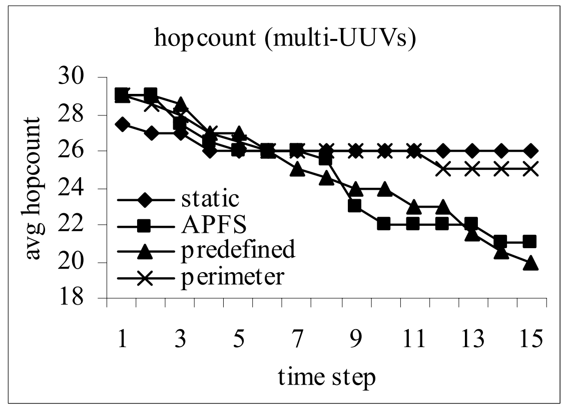

Figure 9: Hopcount during link failure

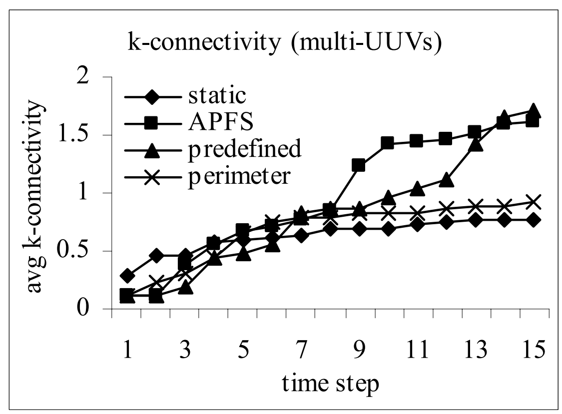

Figure 10: *k*-connectivity during link failure

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