CDS-based Coverage Control algorithm for Buoys based Sensor Networks

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***Abstract*-Underwater acoustic sensor networks (UASN) based on the advances in underwater data collection and observing systems may play an important role in oceanographic research. UASN typically comprises of sensor nodes that are deployed in sufficiently large numbers for data collection, monitoring and surveillance, where sensor nodes are also energy limited without easy way to replenish power unfortunately. Due to severely limited energy constraints of nodes and poor transmission feature in the harsh oceanic environment, how to conserve energy while maintaining network coverage has been one of the most difficult problems. As one special kind of UASN, Buoys based sensor networks (BSN) proposed by ourselves comprises a mass of buoy-based vertical detection chains, which are regard as surface buoy nodes in one planar sea level. Compared with UASN, BSN can extend coverage distance and improve wireless transmission rate, therefore, it is one more promising method to perform oceanic three-dimensional exploration. This paper investigates the utility of a Connected Dominating Set (CDS) based coverage control algorithm for buoys based sensor networks. Traditional CDS-based algorithm maintains a connected virtual backbone of awaking nodes to enable necessary information delivery. Surface buoy nodes belonging to CDS virtual backbone remain awake until the next new round, whereas non-CDS buoy nodes go to low-powered sleep mode. However, how to maintain network coverage of BSN has not been considered. Surface buoy nodes are more sparsely deployed because of their much higher prices, therefore, wireless communication links are prone to break and regions of interest (ROI) are prone to blind monitoring since lack of accurate placement. This paper used CDS-based coverage control algorithm to decide buoys scheduling policy so as to guarantee network reliability and robustness.**

I. INTRODUCTION

To our best knowledge, the ocean covering about two-third of the surface of earth has played an increasingly important role due to resource limitation in the earth, but there is still hugely unexplored vastness of the ocean. Traditional technical methods for oceanic exploration have many disadvantages due to oceanic harsh environments and undiscovered working manners. Underwater Acoustic Sensor Networks (UASN) [1-3], which has received growing interests recently, is a new paradigm acting as the extension of traditional terrestrial wireless sensor networks (WSN). For large-scale UASN, hundreds or thousands of sensor nodes are deployed in a wide underwater area. UASN have many potential applications such as seismic imaging of undersea oilfields, oceanographic data collection and disaster warning because the prefect scalability of UASN ensures that a large interest area can be covered for time-critical applications. Therefore, UASN is becoming increasingly important for oceanographic and other monitoring applications as we strive to explore deeper into our undersea world. UASN typically comprised of sensor nodes that are deployed in sufficiently large numbers for data collection, monitoring and surveillance. The typical framework of UASN is composed of underwater sensor nodes, underwater sink nodes, underwater relay nodes, surface buoys and surface station, etc, as shown in Fig.1. Multi-hop relay transmission manner is used to deliver acquired data from sensor nodes to the sink node. Finally, the simulation results verified the efficacy of the proposed coverage control scheme.

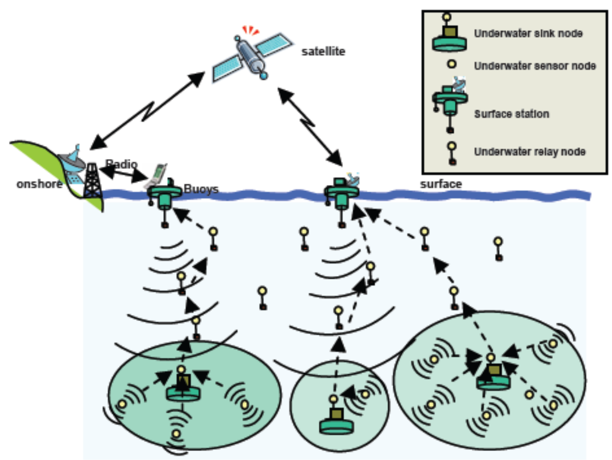

Figure 1. Underwater Acoustic Sensor Networks

Unfortunately, sensor nodes of UASN are energy limited with no easy way to replenish power [4,5]. There are specific technical aspects to realize underwater applications which can't be borrowed from terrestrial sensors networks research such as acoustic communication, higher and extremely variable propagation delay, severely limited bandwidth, etc. Due to severely limited energy constraints of sensor nodes and poor transmission feature in the harsh oceanic environment, how to conserve energy while maintaining network coverage has been one of the most difficult problems.

Moreover, there are too many difficulties in applying underwater acoustic sensor networks in practical. The adverse aqueous environment, the node mobility and the network scale pose grant challenges. Due to limited wireless communication bandwidth and overlong transmission delay of acoustic communication, UASN is not satisfied with many situations

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on oceanic monitoring. Considering these limitations, we proposed one novel concept named as buoys based sensor networks (BSN) to improve network utilization. Fig.2 illustrates the framework of BSN, where buoy nodes float on the offshore plane and deliver information in multi-hop transmission manner. Buoy nodes floating on the offshore plane can use solar cell to replenish energy, moreover, radio frequency wireless communication outperform acoustic communication at the aspect of bandwidth, delay and jitter, therefore, BSN would play a much more important role on oceanic monitoring and observation.

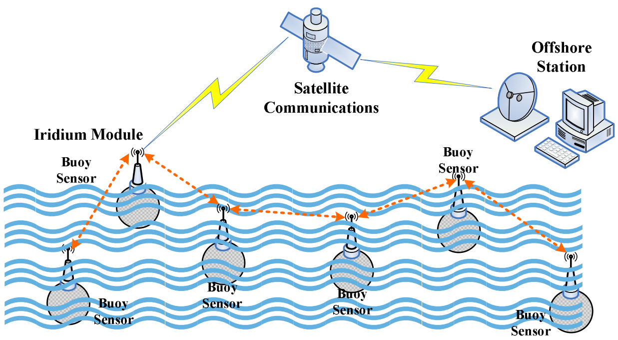


Figure 2. Buoys based Sensor Networks

However, wireless communications between buoys belong to horizontal information transmission, while oceanic observation at different section plane would use buoy-based vertical detection chain shown in Fig.3. With vertical detection chain, it is feasible for vertical orientation observation so as to achieve three dimensional oceanic monitoring. In this paper, we dedicate to study coverage control scheme of buoys based sensor networks.

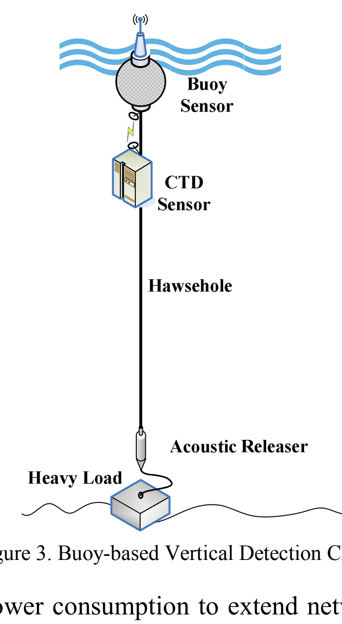


Figure 3. Buoy-based Vertical Detection Chain

Reducing power consumption to extend network lifetime is one of the most important challenges for BSN. One promising approach to conserving energy is to keep only a minimal number of buoy sensors active and put others into low-powered sleep mode, while active buoy sensors can maintain communication connectivity and cover target region completely. However, computing such minimal active buoy sensor set is NP-hard. In ref [6-9], several heuristic algorithms and ambitions algorithms are investigated for WSN, but none of them is suitable for BSN. This paper investigates the utility of a Connected Dominating Set (CDS) [10,11] based coverage control algorithm for buoys based sensor networks. The connected dominating set S of graph G is defined as the connected subset of V such that a buoy node in V-S is adjacent to at least one buoy sensor in S. The traditional CDS-based algorithm maintains a connected virtual backbone of awaking nodes to enable necessary information delivery. Buoy nodes belonging to CDS virtual backbone remain awake until the next new round, whereas non-CDS buoy nodes go to low-powered sleeping mode to conserve energy. However, how to maintain network coverage of BSN has not been considered at the same time. To our best knowledge, buoy nodes are more sparsely distributed when deployed because of their much higher prices, therefore, wireless communication links are prone to break and regions of interest (ROI) are prone to blind monitoring because of lack of accurate placement. Ultimately, sensing coverage and network connectivity of BSN is hard to guarantee. In this paper, we are dedicating to use CDS-based coverage control algorithm to determine buoy sensor scheduling policy so as to guarantee network reliability and robustness.

II. Methodology

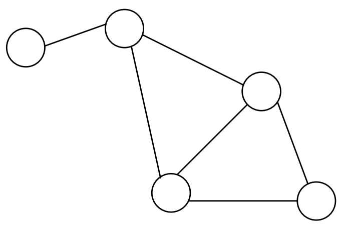
Compared with traditional sensor networks, there are many important limitations such as narrow bandwidth, frequent unpredictable temporary loss, large and variable propagation delay, limited energy specially availability due to difficulty in recharging battery in BSN. To conserve energy, one important way to conserve energy is to control the topology of BSN such that redundant buoy nodes can go to low-powered sleep, while buoy nodes belonging to the CDS remain awake. Buoy nodes only periodically wake up for environment sensing and event generation. However, network coverage guarantee can't be maintained due to sparse deployment of BSN. Therefore, in this paper, we are dedicating to investigate how to maintain a virtual buoy backbone using CDS concept while maintaining network coverage ratio to perform sensing tasks.

To facilitate discussion of the CDS-based coverage control algorithm, we consider a BSN model in which buoy nodes are arbitrarily deployed in a two dimensional rectangle sea level plane. In fact, BSN belong to the three dimensional plane, however, the vertical dimension is moored by vertical detection hawsehole and therefore two dimensional plane model is enough for mathematical analysis. Buoys of BSN can be represented by an undirected simple graph $G(V,E)$ with a set of vertices $V(G)$ and edges $E(G)$. A unique ID is assigned to each buoy node. Moreover, the residual energy level of buoy node i which is denoted as E_i can be monitored in a real-time way. The coverage region of each buoy node is assumed as a

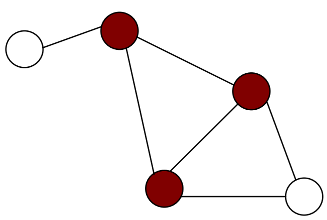
Boolean sensing model, where the sensing region is a circle region with maximum sensing radius R_{max}. In practice, buoy nodes of BSN are mobile following sea current, nevertheless, this paper regards them as static approximately for simpleness.

The Dominating Set S of graph G is defined as the subset of V such that a node in V-S is adjacent to at least one node in S. The Connected Dominating Set (CDS) S is defined as a DS of G that induces a connected sub-graph. In the case of BSN, it is important to minimize the cardinality of a CDS elected in order to reduce the control overhead or collision probability. Finding a DS or a CDS with minimum cardinality is a NP-hard problem [12].

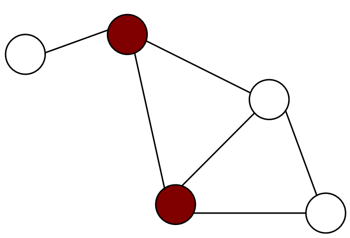
For example, in Fig.4 (a), there is a connected graph G with 5 buoy sensor nodes and 6 edges. In Fig.4 (b), black sensor nodes form a connected dominating set of original graph G, and one set of minimum CDS with only 2 black buoy nodes is exhibited in Fig.4 (c). In a general way, there are multiple kinds of DS and CDS for a certain connected graph, but the major objective is to find a minimum CDS satisfying certain applicable requirements.



(a) Connected graph G



(b) Connected dominating set of G



(c) Minimum CDS

Figure 4. CDS of graph G

The notations of coverage and coverage ratio of BSN are defined as follows,

Definition 1. (Coverage): Given a set of buoy nodes N and a ROI Z, each point in the given ROI is covered by at least one buoy nodes. A point p is covered by a buoy node m is defined the Euclidean distance between p and m is less than R_{max}, the maximum sensing radius of the buoy sensor.

Definition 2. (Coverage Ratio): The ratio between the area of Coverage region and the whole ROI Z.

As indicated in Fig.5, there are 5 buoy nodes arbitrarily deployed in a two dimensional rectangle plane ROI. The sensing region of one node is a circle with radius Rmax. The covered area and uncovered area of 5 buoy nodes are described obviously.

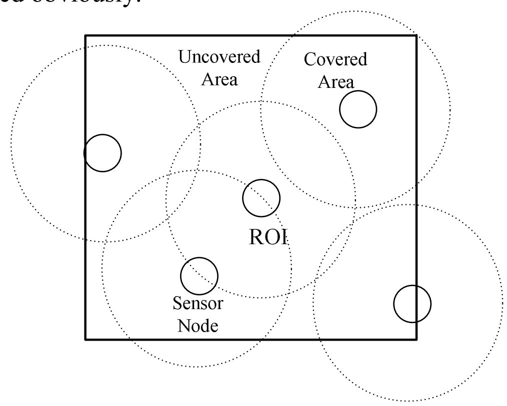


Figure 5. Coverage instance of graph G

III. CDS-BASED COVERAGE CONTROL ALGORITHM

The CDS-based coverage control algorithm proposed in this paper comprises of two phases in one round (Fig.6), i.e., Coverage Control Interval and Data Transmission Interval. Coverage control interval is used to distinguish CDS nodes with non-CDS nodes by CDS-based coverage control algorithm, and then determine different working mode of buoy nodes: awake or sleep mode. Consequently, all buoy nodes come into data transmission interval and begin to delivery sensory information until round interval T.

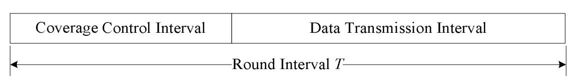


Figure 6. Working Round

The coverage control interval is divided as three phases:

In the first phase named as Neighbor Discovery, each buoy node broadcasts its own geographical information and residual energy ratio to all its 1-hop neighbors and each buoy node maintains a local neighbor information table. The residual energy ratio is defined as the ratio between the residual energy and initial energy of buoy nodes, represented in the range (0, 1). Buoy node with higher remaining energy will have a higher priority.

With this information, in the second phase, each buoy node determines its own CDS or non-CDS decision using Wu algorithm [13]. However, Wu algorithm belongs to one of centralized algorithms, therefore, all calculations are operated by the sink node. Weight value of Wu algorithm running in the sink node is defined in Equation (1),

$$\omega(i) > \omega(j) \Leftrightarrow E(i) > E(j) \text{ or } E(i) = E(j) \,\&\, id(i) > id(j) \quad (1)$$

where $E(i)$ and $E(j)$ denote the residual energy of buoy node i and j respectively, $id(i)$ and $id(j)$ denote ID number of buoy node i and j respectively. It is obvious that the weight value of buoy node is positive correlation with node residual energy, and the ID value of buoy node is the second factor for the weight parameter.

For example, one maximal residual energy CDS topology result is described in Fig.7 (a). There are five sensor nodes 1 to 5 in the BSN, buoy node 2 and buoy node 3 are elected to be CDS member with maximal residual energy CDS topology algorithm.

In the third phase, ROI coverage control scheme will be operated on each buoy node based on CDS virtual backbone constructed in the second phase. With traditional CDS-based topology control scheme, network connectivity can be guaranteed, nevertheless, network coverage ratio can't be guaranteed.

It is assumed that the sink node of BSN has the ability of monitoring all the ROI, therefore, sink node can obtain detailed information of each grid in the ROI. At first, coverage degree C_i of sensor node i is defined as follows,

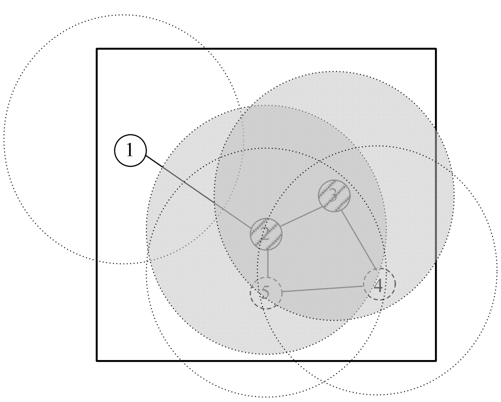
Definition 3. (Coverage Degree): The proportion between the area of covered grid within circle around sensor node and circular area $\pi R_{\max}^2$.

Obviously, the coverage degree of CDS nodes equals to 1 and the coverage degree of non-CDS nodes ≤ 1 . The main idea of proposed coverage control is marking some sensor nodes with lower than average coverage degree of Non-CDS nodes to CDS, as illustrated as follows,

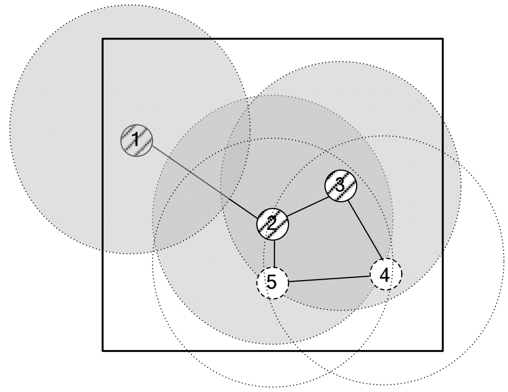
$$C_i \leq \frac{1}{N}\sum_{j=1}^{N} C_j (n_j \in \text{Non-CDS}) \qquad (2)$$

The result of coverage control based CDS topology is shown in Fig.7 (b).

Consequently, all the CDS nodes come into alive state and all the non-CDS nodes come into low-powered sleep state until a periodic round interval time T. In essential, the objective of proposed algorithm is to find an optimal subset of buoy nodes while these buoy nodes can preserve network coverage and maintain communication connectivity, which is an energy efficient coverage-preserving buoy node scheduling problem.



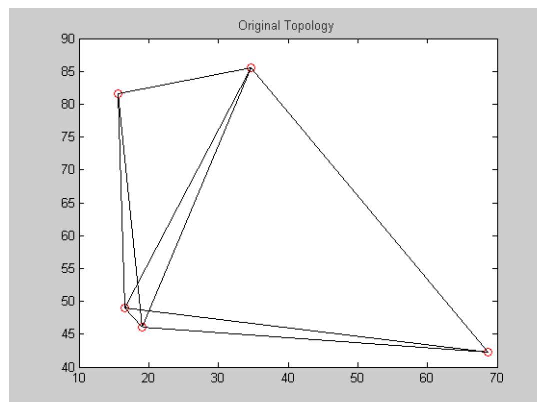
(a) Maximal residual energy based CDS topology



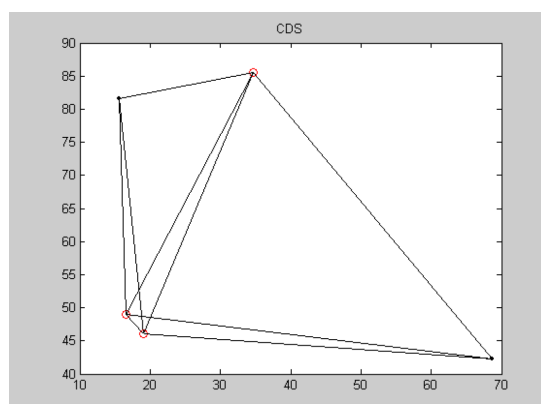
(b) Network coverage control based CDS topology
Figure 7. Example of CDS-based coverage control

IV. SIMULATIONS

Finally, simulations to verify CDS-based coverage control algorithm of BSN are operated on MATLAB software [14]. Original topology and topology results by CDS-based coverage control algorithm are compared in Fig.8.



(a) The original topology



(b) The CDS-based topology

Figure 8. Topology by CDS-based coverage control

Apparently, due to a few non-CDS nodes working in low-powered sleep mode, CDS-based coverage control algorithm would outperform original topology at the aspect of energy conservation comparisons.

Due to the time, we didn't do simulation of much larger scale BSN. In our future simulations, more sophisticated topology will be induced to study algorithm's efficiency with change of network scale, moreover, calculate and compare network coverage degree of different scenes.

V. CONCLUSIONS

In this paper, a novel oceanic exploration facility named as buoys based sensor networks is proposed to improve the utility of UASN. Meanwhile, a novel CDS-based coverage control algorithm is proposed to maintain a virtual backbone using connected domain set while maintaining network coverage ratio. Buoy nodes not belonging to CDS could keep low-powered sleeping status to conserve extremely limited energy of BSN, so as to improve network lifetime of BSN. The simulation results verified the performance of proposed algorithm. Our future work is to look for a suitable and distributed coverage control algorithm to reduce network overhead farther.

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