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Placement of multiple mobile data collectors in underwater acoustic sensor networks

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***Abstract*—For the sake of maximizing the network lifetime, we propose a novel placement scheme for mobile data collectors in Underwater Acoustic Sensor Networks (UASNs). Our scheme is based on a 3D architecture, in which on-the-surface data collectors gather data from underwater sensors and relay them to an on-shore sink. We divide the lifetime of the network into fixed length rounds and move the data collectors to new locations at the beginning of each round.**
We formulate the problem as an Integer Linear Program (ILP) and use an ILP solver to find the optimal placement of data collectors together with the multi-hop routing paths to deliver data from underwater sensors to data collectors. Our work is a pioneering effort in the placement of mobile data collectors in three-dimensional UASNs. Comprehensive experiments show that our scheme prolongs the lifetime of the network significantly as compared to other data collector placement schemes.

I. Introduction

Underwater acoustic sensor networks have prominent potential for environmental monitoring and oceanographic data gathering. Most of the work in underwater sensing and data collection is based on wired networks (e.g., the work in [1]), which demand high cost and significant engineering effort. Recently, attention has been directed to acoustic networks because of their potential to provide low-cost, distributed underwater monitoring [2] [3].

Underwater acoustic sensor devices are battery-operated and, hence, untethered in terms of both power and communication. This enabled a new generation of large-scale, untethered, unattended sensor networks suitable for a wide range of scientific, environmental, and military applications. However, as a result of the limited energy supply of sensor nodes, prolonging the lifetime of UASNs has become crucial for UASNs to deliver their full potential and to enable this variety of fundamental applications. A few Medium ACcess (MAC) and routing protocols (e.g., the work in [2],[4], and [5]) have been proposed to alleviate the effect of energy limitations at individual sensor nodes. However, they fail to solve topology-related problems; with multi-hop communication, nodes near data collectors become bottlenecks and with single-hop communication, nodes far from data collectors deplete their energy very quickly. We argue that such topology-related problems are hard to overcome when data collectors are stationary. Therefore, we propose a scheme that exploits data collector mobility to make a uniform energy consumption across the network and to prolong its lifetime.

Our scheme divides the lifetime of the network into fixed length rounds (e.g., hours, days, or weeks) and moves the data collectors, which can be Autonomous Unmanned Vehicles (AUVs), to new locations at the beginning of each round. Relocation of data collectors will require new routing paths to deliver data from sensor nodes to data collectors. In this paper we formulate the problem of finding the optimal routing and placement of data collectors as an ILP, and we use an ILP solver with a constant time limit to find near-optimal solutions.

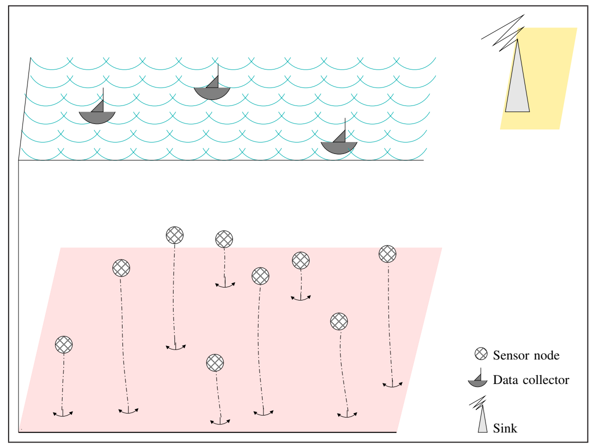

Fig. 1. 3D architecture for UASNs (adapted from [9]).

The benefits of data collectors' mobility in terrestrial sensor networks have been explored and some promising mobility planning schemes have been proposed [6][7][8]. However, those schemes have aimed at locating the data collectors at predefined spots in the sensing field or at the boundary of the network. These constraints do not apply to UASNs where data collectors are free to go virtually anywhere on the surface of the ocean. Moreover, the three-dimensional nature of UASNs imposes another challenge to the problem. To the best of our knowledge, this paper introduces one of the first proposals for the placement of mobile data collectors in three-dimensional UASNs.

The remainder of the paper is organized as follows. Section II describes the model of the system and gives a formal problem definition. In Section III, we present our placement scheme. Section IV shows the experimental results. Finally, in Section V, we conclude by summarizing the contributions and pointing out some related future research directions.

II. System model and problem definition

We consider an UASN consisting of N sensor nodes and R data collectors. Each sensor node collects data from the surrounding environment and sends the collected data to one of the collectors either directly or through other nodes (i.e., multi-hop communication). We follow the three-dimensional architecture proposed in [9]. In this architecture, data collectors are equipped with a radio transceiver to communicate with an on-shore sink, and an acoustic transceiver to communicate with underwater sensors. While data collectors stay on the surface to keep the link with the sink, sensor nodes, which are equipped with acoustic transceivers, float at different depths to carry out the sensing mission. This architecture is shown in Fig. 1.

We assume that the transmission range of an acoustic transceiver can be adjusted to a constant number of levels (i.e., variable, discrete transmission ranges). The topology of the network is modeled as a weighted graph $G = (V, E)$, where $V = \{n_0, n_1, ..., n_{N-1}\}$ is the set of N sensor nodes, and $(i, j) \in E$, if sensor nodes n_i and n_j can communicate with each other directly (i.e., their separation is not more than the maximum transmission range). W_{ij} denotes the weight of the link (i, j) which is the Euclidean distance between senor nodes n_i and n_j; the energy consumption over the link (i, j) is a function of W_{ij}. Each sensor node n_i has a data generation rate G_i. G_i is the number of data units generated by node n_i per time unit.

Our scheme is independent of the underlying MAC protocol. We assume a capacity limit for each sensor node which limits the number of data units that can be transmitted by a sensor node during one round. The capacity of a sensor node n_i is denoted by C_i. This parameter can be adjusted to comply with any constraints imposed by any MAC protocol. While this capacity constraint is applicable to communication links rather than individual nodes, to simplify the presentation of the paper, we will limit ourselves to capacity constraints on individual nodes.

In this paper we assume that data generation rates, residual energy, and locations of all sensor nodes are known in advance. We also assume that data collectors are not energy constrained as they can be easily recharged [10]. Without loss of generality, we define the lifetime of the network as the time until the first sensor node dies. Yet other definitions (e.g., the time until a particular proportion of the sensors die) can be equally used in our scheme.

Problem definition

The problem can be formulated as follows:
The lifetime of the network is divided into equal length rounds. At the beginning of each round, find the optimal locations of R data collectors together with the routing paths to deliver the generated data from all sensor nodes to data collectors. The objective is to maximize the minimum residual energy at the end of the round. Data collectors can be placed anywhere on the surface of the water.

III. Data collectors placement

A data collector may be placed anywhere on the surface of the water as long as it is within the acoustic transmission range of at least one sensor node. Since each sensor node has a discrete number of transmission levels, its transmission range can be viewed as a set of spheres: one sphere for each transmission level. Further, since data collectors are placed on the surface of the water, we should find the intersection of these spheres and the surface of the water. Without loss of generality, we let the plane $z = 0$ represent the surface of the water (where the $z-$ axis represents the depth). Then, the intersection of a sphere centered at a point (a, b, c) with a radius of r and the plane $z = 0$ is:

- ϕ, the empty set, if $r^2 - c^2 < 0$.
- A circle centered at a point $(a, b, 0)$ with a radius of $\sqrt{r^2 - c^2}$, if $r^2 - c^2 \geq 0$. We call such a circle a *surface circle*.

Each sensor node will have at most one surface circle for each transmission level. And since the placement will be made on the surface of the water, we can focus on these surface circles rather than the transmission spheres, i.e., the problem becomes two-dimensional. So let us say each sensor node n_i has γ_i surface circles $\{\zeta_i^0, \zeta_i^1, ..., \zeta_i^{\gamma_i - 1}\}$.

The first challenge now is the infinite search space for data collector locations; the search space involves every single point inside any surface circle. The first step in our scheme is to make the search space finite without affecting the quality of the solution. To explain our method of finding such a finite search space, we recall the notions of complete sets, overlapping regions, and Maximal Overlapping Regions (MORs), which we used in the context of terrestrial two-dimensional sensor networks [11]. For the sake of completeness, we provide the following definitions.

Definition A finite set of points $\mathcal{P}$ is *complete* if and only if it satisfies the following property:
There is an optimal placement of data collectors in which each data collector is placed at a point in $\mathcal{P}$.

We aim at finding such a complete set in order to make the placement problem a discrete optimization problem. Moreover, since the computational complexity of the solution will be proportional to the cardinality of that set, we should find a complete set with reasonably small size.

Definition An *overlapping region* is a region where a nonempty subset of surface circles overlap. For an overlapping region $\mathcal{O}$, let $\mathcal{S}(\mathcal{O})$ denote the subset of surface circles that overlap at $\mathcal{O}$.

Definition An overlapping region $\mathcal{O}$ is *maximal* if there is no overlapping region $\mathcal{F}$ where $\mathcal{S}(\mathcal{O}) \subset \mathcal{S}(\mathcal{F})$.

We next show that a complete set can be derived from the set of MORs. We first state the following lemma without proof.

Lemma 1: For every overlapping region $\mathcal{O}$, there exists a MOR $\mathcal{F}$, such that $\mathcal{S}(\mathcal{O}) \subseteq \mathcal{S}(\mathcal{F})$.

Then, we deduce the following theorem.

Theorem 1: A set $\mathcal{P}$ that contains one point from every MOR is complete.

Proof: To prove this theorem, it suffices to show that for any arbitrary placement $\mathcal{N}$ we can construct an equivalent placement $\mathcal{N}^*$ in which every data collector is placed at a point in $\mathcal{P}$. Let us say that in $\mathcal{N}$, a data collector $\mathcal{B}$ is placed such that it is inside a subset of surface circles $\mathcal{H}$. It is obvious that there exists an overlapping region $\mathcal{O}$, such that $\mathcal{H} \subseteq \mathcal{S}(\mathcal{O})$. From the previous lemma, there exists a MOR $\mathcal{F}$, such that $\mathcal{S}(\mathcal{O}) \subseteq \mathcal{S}(\mathcal{F})$. In $\mathcal{N}^*$, we place $\mathcal{B}$ at the point in $\mathcal{P}$ that belongs to $\mathcal{F}$, so that $\mathcal{B}$ is placed at a point in $\mathcal{P}$ and is still inside the region where all surface circles in $\mathcal{H}$ overlap. Repeating for all data collectors, we construct a placement $\mathcal{N}^*$ which is equivalent to the placement $\mathcal{N}$. ∎

A. Finding MORs

To find all MORs, we need to find the arrangement of surface circles. Let ζ_i^k denote a surface circle belonging to a sensor node n_i. If p is an intersection point of the boundaries of ζ_i^k and another surface circle ζ_j^l, let $succ_i^k(p)$ ($succ_j^l(p)$) denote the intersection point incident to ζ_i^k (ζ_j^l) that comes right after p according to a clockwise order, and let $other_i^k(p) = (j, l)$ and $other_j^l(p) = (i, k)$. The arrangement of circles is a data structure by which for any intersection point p of ζ_i^k, we can get $succ_i^k(p)$ and $other_i^k(p)$ in $O(1)$ time. By walking over the boundary of a surface circle ζ_i^k in a clockwise direction, intersection points incident to ζ_i^k can be classified into three groups: *entry points*, *exit points*, and *tangent points*. An entry point is one at which we enter another surface circle. An exit point is one at which we leave another surface circle. A tangent point occurs if two surface circles intersect at exactly one point. Fig. 2 gives an example of four circles (a,b, c, and d) where the intersection points incident to the circle a are classified. Now, it is straightforward to realize the following observation.

Observation An overlapping region $\mathcal{O}$ is maximal if and only if it satisfies one of the following properties:

1) $\mathcal{O}$ is a tangent point.
2) By walking on the boundary of $\mathcal{O}$ in a clockwise direction, all intersection points (if any) are exit points AND no circle lies entirely inside $\mathcal{O}$.

To check whether some circle lies entirely inside an overlapping region, we add *defect points* to the arrangement of circles. A circle may add at most one defect point. To find the defect point of a circle ζ_i^k centered at a point (x_i, y_i), we find points that:

1) lie at the intersection of the line $y = y_i$ and another circle ζ_j^l.
2) are outside and to the right of ζ_i^k.

Amongst those points that satisfy these two conditions, we take the point p which is the closest to (x_i, y_i). Let us say p lies at the boundary of a circle ζ_j^l. Then, if (x_i, y_i) is inside ζ_j^l, p is added as a defect point on ζ_j^l. Note that such a point does not necessarily exist for all surface circles, i.e., some circles may not add any defect point. Fig. 3 shows an example of an overlapping region which is not maximal because of entry points (a), a MOR (b), and an overlapping region which is not maximal because of a defect point (c). Note that the whole area of the small circle in Fig. 3 (c) is a MOR. In what follows, Algorithm 1 finds the arrangement of surface circles together with the defect points; it runs in $O(n^2 \log n)$ time. Algorithm 2 tests whether an overlapping region is maximal or not. Algorithm 3 uses Algorithms 1 and 2 to construct a complete set $\mathcal{P}$ by finding all MORs. Note that the Boolean array $Flag(p, i)$ is used to guarantee that we do not check the same overlapping region more than once. The overall complexity of Algorithm 3 is $O(n^2 \log n)$.

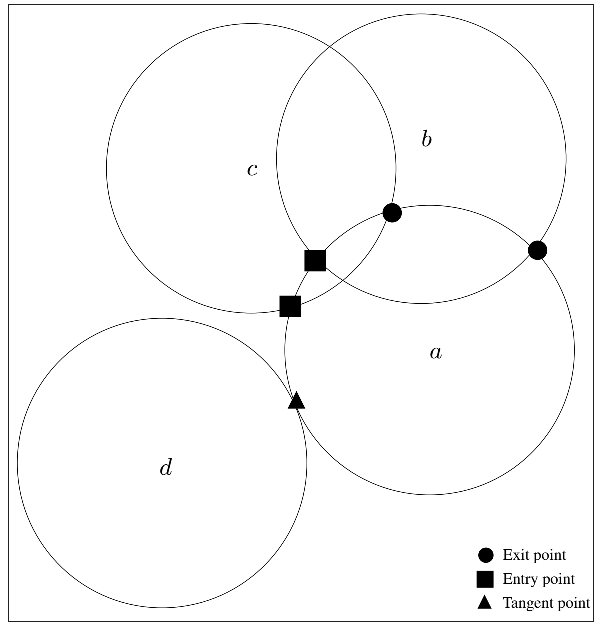

Fig. 2. Entry points, exit points, and tangent points.

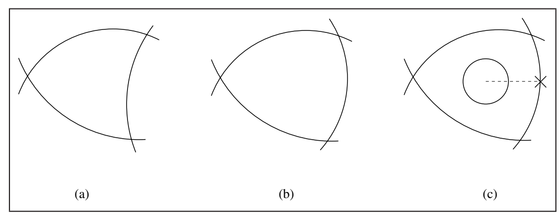

Fig. 3. Overlapping regions, MORs, and defect points.

B. ILP formulation

Once we obtain the set $\mathcal{P} = \{p_0, p_1, ..., p_{M-1}\}$, which contains a point from each MOR, the problem of finding the optimal locations of R data collectors and the flow paths from sensor nodes to data collectors can be formulated as an ILP. We define the following constants and variables.

Constants:
G_i is the data generation rate of sensor node n_i.
$N(i)$ is a set of indices such that $j \in N(i)$ if n_j is within the transmission range of n_i (i.e., n_j is a neighbor of n_i).
$M(i)$ is a set of indices such that $j \in M(i)$ if the point p_j,

Algorithm 1: Arrangement of surface circles.

```
Procedure FindArrangement( )
foreach sensor node n_i do
    Find all surface circles corresponding to n_i;
end
Find all points where the boundaries of two surface
circles intersect;
Find all defect points;
foreach surface circle ζ_i^k do
    Sort all intersection points and defect points incident
    to ζ_i^k in a clockwise order;
end
```

Algorithm 2: Testing whether an overlapping region is maximal or not.

```
Function Maximal(ζ_i^k: a circle, p: a point)
Input:  A surface circle ζ_i^k and a point p, which could
        be an intersection point or a defect point, incident
        to ζ_i^k.
Output: True if a MOR is found, and False otherwise.
if Flag(p,i) = 1 OR p is an entry point with respect to
ζ_i^k OR p is a defect point then
    return False ;
end
if p is a tangent point then
    return True ;
end
Flag(p,i) := 1;
q:=p;
(j,l):=other_i^k(p);
p:=succ_j^l(p);
i:=j;
k:=l;
while p ≠ q do
    if Flag(p,i) = 1 OR p is an entry point with respect
    to ζ_i^k OR p is a defect point OR p is a tangent point
    then
        return False ;
    end
    Flag(p,i) := 1;
    (j,l):=other_i^k(p);
    p:=succ_j^l(p);
    i:=j;
    k:=l;
end
return True ;
```

Algorithm 3: Finding all MORs.

```
Procedure FindMORs( )
Output: A set P that contains one point from every
        MOR.
P:=φ ;
FindArrangement( );
foreach intersection point p which is incident to two
surface circles ζ_i^k and ζ_j^l do
    Flag(p,i):=0;
    Flag(p,j):=0;
end
foreach surface circle ζ_i^k do
    foreach intersection point p incident to ζ_i^k do
        if Maximal(ζ_i^k,p) then
            P:=P ∪ {p};
        end
    end
end
```

which belongs to a MOR, is within the transmission range of n_i.
$B(i)$ is a set of indices such that $j \in B(i)$ if the point p_i, which belongs to a MOR, is within the transmission range of n_j.
N is the number of sensor nodes.
R is the number of data collectors.
M is the number of MORs.
E_i is the residual energy of sensor node n_i.
$E_{Tr}(d)$ is the energy consumed to send one data unit to a destination which is d units away from the source.
E_{Rc} is the energy consumed to receive one data unit.
W_{ij} is the Euclidean distance between sensor nodes n_i and n_j.
D_{ij} is the Euclidean distance between a sensor node n_i and a point p_j, which belongs to a MOR.
C_i is the traffic capacity of sensor node n_i (i.e., the maximum number of data units that can be relayed by n_i per round).
α is the weight assigned to the minimum residual energy.
β is the weight assigned to the total consumed energy.
Variables:
$l_i = 1$ if a data collector is placed at p_i, and $l_i = 0$ otherwise.
If $j \in N(i)$, f_{ij} is the flow from sensor node n_i to sensor node n_j (i.e., the number of data units to be sent from n_i to n_j per round).
If $j \in M(i)$, h_{ij} is the flow from sensor node n_i to the data collector at p_j (if no data collector is placed at p_j, h_{ij} will be set to 0).
E_{min} is the minimum residual energy over all sensor nodes at the end of the round.
E_{total} is the total consumed energy during the round.

Our policy of maximizing the lifetime is to maximize the minimum residual energy (i.e., E_{min}) at the end of each round. However, it is easy to see that more than one solution may have the same optimal value for E_{min} but possibly different values for E_{total}. Amongst those solutions for which E_{min} is maximized, we want to pick the one with the minimum E_{total}. In order to do so, we have the following objective function:
$\alpha\, E_{min} - \beta\, E_{total}$,
which is composed of a linear combination of E_{min} and E_{total} with a much higher weight given to E_{min} (i.e., $\alpha \ggg \beta$).
While a similar ILP formulation was first introduced in [6] for 2D terrestrial networks, the authors in [6] assume the existence of a set of feasible locations (i.e., the set $\mathcal{P}$ which we construct in the previous subsection). Furthermore, our objective

Maximize $\alpha\, E_{min} - \beta\, E_{total}$
s.t.,

$$\sum_{j\in N(i)} f_{ij} + \sum_{j\in M(i)} h_{ij} \le C_i, 0 \le i < N \tag{1}$$

$$\sum_{j\in N(i)} f_{ij} + \sum_{j\in M(i)} h_{ij} - \sum_{j\in N(i)} f_{ji} = G_i \quad , \quad 0 \le i < N \tag{2}$$

$$E_i \; - \; \sum_{j\in N(i)} E_{Tr}(W_{ij})\, f_{ij} - \sum_{j\in M(i)} E_{Tr}(D_{ij})\, h_{ij} - \; E_{Rc} \sum_{j\in N(i)} f_{ji} \ge E_{min} \quad , 0 \le i < N \tag{3}$$

$$\sum_{0\le i<N} \Big(\sum_{j\in N(i)} E_{Rc} f_{ji} + \sum_{j\in N(i)} E_{Tr}(W_{ij})\, f_{ij} + \sum_{j\in M(i)} E_{Tr}(D_{ij}) h_{ij} \Big) = E_{total} \tag{4}$$

$$E_{min} \ge 0 \tag{5}$$

$$\sum_{i\in B(j)} h_{ij} \le l_j \sum_{0\le i<N} G_i, 0 \le j < M \tag{6}$$

$$\sum_{0\le i<M} l_i = R \tag{7}$$

$$l_i \in \{0, 1\}, 0 \le i < M$$

Fig. 4. ILP formulation.

function is different from the one in [6]. Our scheme prolongs the lifetime by maximizing the minimum residual energy over all nodes at the end of each round. Including the work in [6], several existing proposals for different routing and placement problems aim at prolonging the lifetime by minimizing the total consumed energy or minimizing the maximum amount of energy consumed by an individual node. We argue that these schemes are not really suitable for the placement of mobile data collectors. That is because the optimal solution towards such objectives will not change over time and, hence, will not change the locations of data collectors. Residual energy must be taken into account for any mobile data collector scheme as it is the only attribute that changes over time, and the only factor that makes such mobility desirable.

In our scheme an ILP that reflects our policy is to be solved at the beginning of each round in order to move data collectors to new locations. The ILP is shown in Fig. 4. Equation (1) satisfies the traffic capacity constraints and equation (2) guarantees the flow balance. Equation (3) makes E_{min} the minimum residual energy over all sensor nodes (note that we maximize E_{min}). Equation (4) sets E_{total} to the total energy consumption. Equation (5) guarantees that the energy expenditure of any sensor node is not more than its current residual energy. Equation (6) guarantees that if no data collector is placed at p_j (i.e., l_j=0), no flow is sent to p_j. Equation (7) satisfies the constraint that only R data collectors are available.

It is important to note that this ILP can be modified to handle more complex capacity constraints (e.g., giving different weights to different links incident to a single node). We show a general case here to simplify the presentation.

IV. Experimental results

We conducted some experiments to compare our scheme with two other schemes. The first one is the FIXED scheme in which data collectors are static and are placed randomly on the surface of the water. In the FIXED scheme, we use a similar ILP to find near-optimal routing paths for a given placement. The second scheme we compare with is a mobile one in which the objective is to Minimize the Maximum (MM) amount of energy consumed by one node. Our scheme is denoted by MR which stands for Maximize the minimum Residual energy.

In our simulations we assume three transmission levels: 5 km, 2.5 km, and 1 km. The WHOI modem [12] transmits over 5 km at 10W with a data rate of 220 bits/sec. Other acoustic modems have slightly different energy consumption settings [10]. For simulation purposes, we set our energy consumption parameters to be compatible with those of the WHOI modem and with the general energy consumption model described in [3]. So we set $E_{Tr}(5\text{ km}) = 20$ mJ/bit, $E_{Tr}(2.5\text{ km}) = 5$ mJ/bit, $E_{Tr}(1\text{ km}) = 2$ mJ/bit, and $E_{Rc} = 1$ mJ/bit. Every sensor node has an initial energy of 2×10^5 J, and generates 64 bytes/hour. The round length is one day. The capacity of sensor nodes is uniformly distributed between 1000 and 2000 bytes/hour. Our simulations involve networks of sizes 100 and 200 sensors. In each network, we tested different scenarios of one, two, three, four, and five data collectors. For each scenario, we generate 20 random samples and take the average. To solve the ILP, we use *lp_solve* 5.5 [13] with a timeout of 20 minutes.

Fig. 5 shows the lifetime comparison between different schemes in networks of 100 sensor nodes randomly deployed in a 20 × 20 × 2 km^3 volume (the maximum depth is 2 km). Fig. 6 shows a comparison of the average energy consumed per byte. Fig. 7 shows the simulation results in networks of 200 sensor nodes randomly deployed in 30 × 30 × 2 km^3 volume. Fig. 8 shows a comparison of the average energy consumed per byte. Note that the different schemes have similar energy consumption per byte, yet our scheme has a much longer lifetime. This is due to the load balancing effect that is exercised in our scheme and due to the consideration made for residual energy. Using different values for the ILP solver timeout, different sensor densities, and different number of data collectors have shown similar trends.

V. Conclusion

We propose a scheme for finding near-optimal routing and placement of mobile data collectors in UASNs. The novelty of the proposed scheme stems from solving a three-dimensional placement problem in which a data collector can be placed anywhere on the surface of the water and from finding a complete, finite search space for data collector locations. We use a novel objective function that takes into account both the current residual energy and future energy expenditure of each

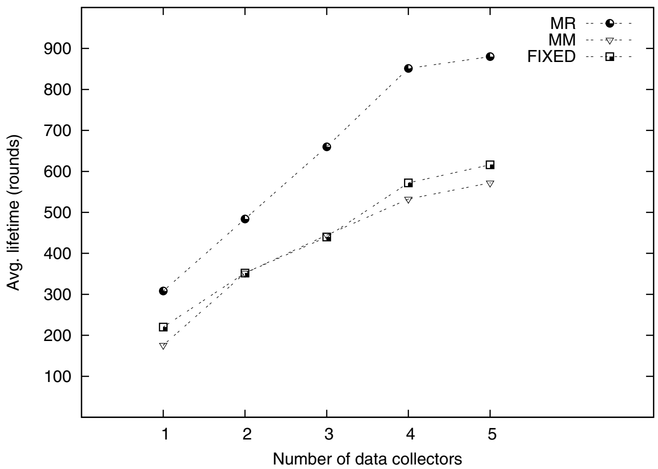

Fig. 5. Lifetime comparison results in networks of 100 sensor nodes.

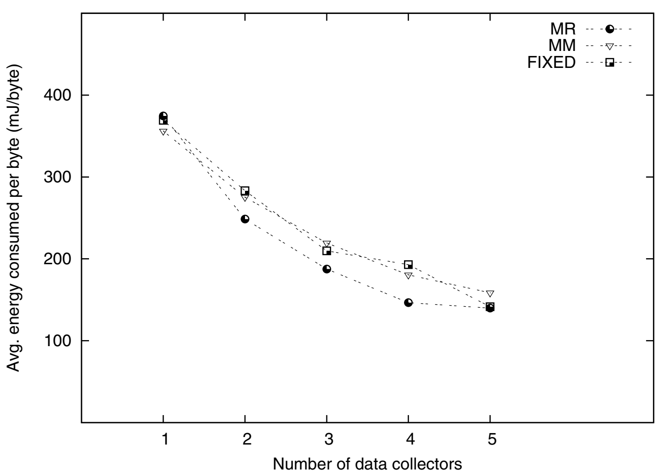

Fig. 6. A comparison of the average energy consumption per byte in networks of 100 sensor nodes.

sensor node. Simulation results show that our scheme has the potential to prolong the lifetime of a UASN significantly as compared with another static scheme and a mobile scheme that does not consider the residual energy of nodes.

We are currently extending our scheme to a more general UASN architecture where data collectors can go below the surface of the water to get closer to sensor nodes and to avoid having bottlenecks among sensor nodes near the surface. Such an architecture demands a schedule for data collectors that need to go up to the surface periodically in order to report data to the sink.

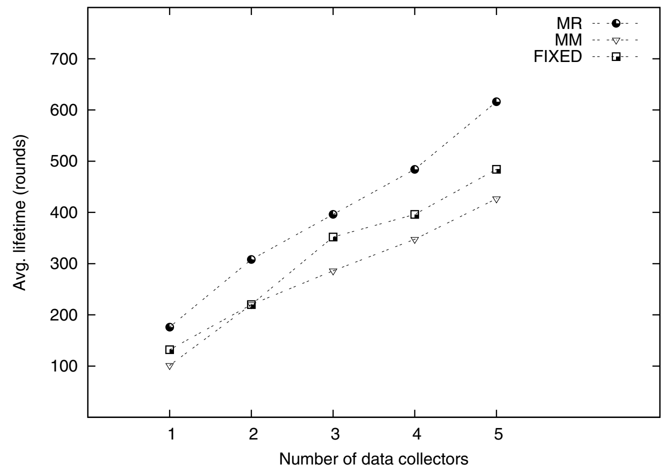

Fig. 7. Lifetime comparison results in networks of 200 sensor nodes.

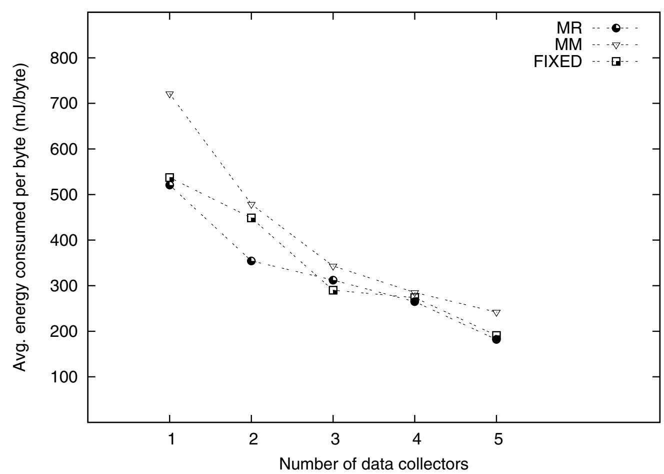

Fig. 8. A comparison of the average energy consumption per byte in networks of 200 sensor nodes.

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