Combined Routing and Node Replacement in Energy-efficient Underwater Sensor Networks for Seismic Monitoring

Arupa Mohapatra, Natarajan Gautam and Richard Gibson

Abstract

Ocean bottom seismic systems are emerging as superior information-acquisition methods in seismic monitoring of petroleum reservoirs beneath ocean beds. These systems use a large network of sensor nodes that are laid on the ocean floor to collectively gather and transmit seismic information. In particular, underwater wireless sensor networks are gaining prominence in continuous seismic monitoring of undersea oilfields. They are autonomous and use wireless acoustic transmission for transferring data. However, the deployment period of such networks extends well beyond the battery lifetimes of the nodes. Hence, in order to ensure continuous monitoring from all node locations, it is required to replace the energy-depleted nodes on the ocean floor. Replacing these nodes at remote undersea locations is very expensive and hence the total node replacement cost in large seismic node networks is extremely high. In this paper, we develop effective joint policies involving routing and node replacement decisions to minimize the replacement costs per unit time. Our routing approach is simple and suitable for this application, and it strives for energy efficiency at all times. We propose a few node-replacement policies and compare their performances when they are combined with our proposed routings.

Index Terms

Underwater sensor network, energy-efficient routing, node replacement, seismic monitoring, ocean bottom seismic system

A. Mohapatra and N. Gautam are with the Department of Industrial and Systems Engineering and R. Gibson is with the Department of Geology and Geophysics at Texas A&M University, College Station, TX 77843 USA (email: arupa@tamu.edu; gautam@tamu.edu; gibson@tamu.edu)

I. INTRODUCTION

Over the last several years, there has been a significant rise in interest in underwater wireless sensor networks for a wide range of applications (e.g. seismic monitoring of undersea oilfields (Heidemann *et al.* [1], Li *et al.* [2]), marine environment monitoring (Akyildiz *et al.* [3], Vasilescu *et al.* [4]) and offshore surveillance (Akyildiz *et al.* [3], Pompili and Melodia [5])). An increasing number of commercial applications in this area have led to steady advances in underwater communication and networking as well as in offshore exploration and deployment procedures. As underwater sensor networks have begun to be deployed in many applications, cost-efficiency in the operation of these networks has now become an important issue. In this paper, we consider strategies for reducing the operating cost in underwater sensor networks used in seismic monitoring of undersea oilfields. Unlike most terrestrial sensor networks, the underwater sensors (also called nodes here) are very expensive and are deployed for prolonged (nearly permanent) monitoring operation. Also, to ensure continuous operation, it is required to replace these nodes when they run out of battery energy. However, given the remote offshore location of the network, the node replacement costs are very high and are a major component of the total operating cost. In this paper, we develop effective policies to minimize this cost in the seismic monitoring application.

A. Seismic Monitoring

Our main motivation comes from the need to use underwater wireless sensor networks in the petroleum industry which is heavily dependent on seismic methods to find various changes in oil and gas reservoirs as responses to production. Ocean bottom seismic systems are emerging as superior information-acquisition methods in seismic monitoring of undersea oilfields. These systems use a large network of sensor nodes (known as Ocean Bottom Seismometers (OBS)) that are laid on the ocean floor to collectively gather and transmit seismic information. At present, a majority of OBS acquisition methods use a wired underwater node network (known as Ocean Bottom Cable (OBC) method [6]) wherein nodes are connected by fiber-optic cables on the ocean floor. However, in this method, installation and operating costs are extremely high. Further, deploying miles of heavy cable and sensor packages on the ocean floor causes substantial damage to the marine environment. Hence as an alternative, some applications have started using autonomous data-storage nodes which are required to be retrieved regularly to collect the data stored in them [7]. However, unlike the cable-based acquisition, the inability of this method to retrieve seismic data in real-time is a major limitation. In fact there is an increasing need for real-time seismic information in the oil industry to improve reservoir management and optimize production. Thus the idea of using nodes with wireless data transmission capability has recently gained interest in this application [1]. This method retains all major benefits of autonomous nodes and provides the opportunity for real-time monitoring.

In this paper, we consider OBS acquisition by a suitable underwater wireless sensor network. We mainly focus on the use of this network for passive seismic monitoring (also known as microseismic monitoring) application where all nodes continuously monitor signals from micro-seismic activities in the undersea reservoir. The ability of passive seismic to monitor dynamic processes in real time has led to its increasing use in recent years (Duncan [8], Martakis *et al.* [9], Maxwell and Urbancic [10]). The underwater passive seismic network can also be used to conduct conventional active seismic surveys to monitor reservoir fluid movements at intervals on the order of several months to a year. In active seismic data acquisition, ‘air gun’ sources generate acoustic waves by injecting compressed air into the sea water. These waves propagate into the earth and the nodes on the seabed (in OBS acquisition) measure the velocity and pressure of the waves reflected from different undersea rock layers. Here the collected data is primarily used to produce a 3D or 4D (time lapse) seismic image of the undersea oilfield.

In an underwater passive seismic network, all nodes continuously sense and transmit information to data-gathering sink nodes via multi-hop wireless transfer. However, as the battery energy available to the nodes is limited, the deployment period (usually 20-50 years) of the network extends well beyond the lifetimes of the nodes. Hence nodes must be replaced on or before complete energy loss in order to ensure continuous monitoring from all node locations. We aim to minimize these node replacement costs which are very high over the period of operation of the network. To achieve this, we employ a combined routing and node replacement policy approach which we describe next.

B. Combined Routing and Node Replacement Policy

The node replacement operation in underwater seismic node networks involves a fixed setup cost per every replacement attempt and an additional cost per every individual node replacement. The fixed setup cost primarily involves sending crew and equipment to the remote off-shore location. This implies that costs can be saved by replacing several nodes together at a time. Note that in case of an extremely high fixed cost, it would be optimal to replace all the nodes in the network when a replacement attempt is made. On the other hand, when this fixed cost component is reasonably low, only replacing nodes as they fail would be cost-effective. In our application, the fixed set-up cost is certainly very high, but the variable cost component for individual node replacement is not negligible either. Hence there is a need for developing an effective replacement policy to minimize the replacement costs. This node replacement policy (or schedule) will specify when to make replacement attempts and which nodes to replace in a every single attempt. However, node replacement decisions alone do not control the replacement costs. Note that the average rate of replacement of every node depends on its energy consumption rate which is primarily dependent on the amount of data transmission handled by the node. Since the data generation rate is fixed at all the nodes, transmission loads are mainly decided by the routing strategy that specifies the distribution of packet transmissions on different routes from each node. Thus the routing method not only need to be energy-efficient, but it must also work well with the replacement policy to minimize the replacement cost. Hence the node replacement costs can be effectively controlled by a combined policy of routing and node replacement decisions.

Both routing and replacement problems have received a lot of attention in the literature, but they have mostly been addressed independent of each other. In particular, many energy-efficient routing algorithms are available for both terrestrial and underwater networks. The majority of these routing algorithms, mostly available for terrestrial sensor networks, can be divided into two main categories. Various routing techniques in the first category try to minimize the overall energy consumption in the network (Heinzelman *et al.* [11], Singh *et al.* [12]). The routings in the second category try to maximize network use by balancing energy consumption throughout the network (Chang and Tassiulas [13], Shah and Rabaey [14]). Further, recent energy-aware routing approaches by Lin *et al.* [15] and Zeng *et al.* [16] consider nodes with renewable energy sources that can replenish energy at a certain rate. For long-lived network applications like seismic monitoring, replacement of nodes is unavoidable since energy conservation through routing (or any other communication protocol) is not sufficient to sustain network operation for the entire deployment period. Hence node replacement in wireless sensor networks has received significant attention recently. Tong *et al.* [17] develop a node replacement policy as well as an algorithm to schedule the replacement of individual nodes in a replacement attempt. Parikh *et al.* [18] develop several node replacement policies to maintain a threshold sensing coverage in wireless sensor networks. There is very limited work available on node replacement in wireless sensor networks and none of the these models consider routing with node replacement. There are various replacement models available in the operations research literature on maintenance of multicomponent systems such as our node network. Kobbacy *et al.* [19] provide a comprehensive review of multicomponent maintenance models developed before 2006. Most of these models consider a distribution function for deterioration of the components. The continuous energy loss of the nodes in our problem is equivalent of such a deterioration process. As the number of states of the system rise exponentially with the number of components, finding an optimal replacement policy for such a system with sizable number of components is computationally infeasible [19]. Recent works by Heidergott [20], Heidergott and Farenhorst-Yuan [21], and L'Ecuyer *et al.* [22] have focused on age replacement policies due to their simplicity and effectiveness. These are state-independent policies where components are replaced when they attain a certain age threshold (equivalently a residual energy threshold for our nodes). The "FRP" and "FRD" policies that we introduce in Section IV.B are indeed threshold-based replacement policies.

Most of the known routing and node replacement techniques for sensor networks are not suitable for our considered seismic monitoring application. The main challenges for routing and node replacement in underwater seismic node networks are: (1) high energy consumption in acoustic transmission, (2) continuous energy consumption by the nodes, and (3) high cost of the node replacement and the economies of scale in the replacement cost structure. Certain aspects of the seismic network operation are also different from those in conventional sensor networks. Note that the flow of seismic information is deterministic due to fixed size of the generated data and its periodic transmission. Also, transmission to only next-hop nodes is considered most reliable due to the noisy underwater environment and the long distance of separation (usually in hundreds of meters) between nodes. Due to the above challenges and specific requirements, we develop new strategies for routing and node replacement in underwater seismic networks.

In this paper, our solution approach (for node replacement cost minimization) combines routing and node replacement policies while taking inputs from both operations research and communication networking literature. Following are the major contributions of our work.

1) Our work is the first of its kind to consider minimizing node replacement costs in continuous seismic monitoring of undersea oilfields using an underwater sensor network.
2) Our solution idea involving joint control of routing and node replacement is also new. Based on this idea, we provide mathematical formulations for minimizing the node replacement costs and also develop effective methods suitable for practical implementation.

The remainder of the paper is organized as follows. In Section II, we provide combined routing and node replacement formulations to minimize node replacement costs in a generic sensor network. Section III outlines the network model and assumptions specific to the seismic monitoring application. In Section IV, we develop effective methods to minimize node replacement cost in our considered seismic node network. We report our computational results in Section V. Finally in Section VI, we present our concluding remarks and some future research directions in the domain of this problem.

II. COMBINED ROUTING AND NODE REPLACEMENT IN A GENERIC SENSOR NETWORK

In this section, we provide mathematical formulations (based on our combined routing and node replacement approach) for minimizing node replacement costs in a generic sensor network. We will consider the special case for seismic monitoring application in Section III onwards.

Consider a network of N similar nodes which will be utilized over a long time period, say T days. Let the data-gathering sink node be denoted as the $(N+1)$-st node. In every data collection *round*, node-i ($i = 1, \cdots, N$) generates s_i number of packets and sends them to the sink node via multihop routing. Assume that there are D rounds of data collection in a day. Let U_i be the set of nodes from which node-i can directly receive data and let V_i be the set of nodes to which node-i can directly transmit. Node-i consumes E_{ij}^T amount of energy to transmit a packet to node-j ($j \in V_i$). Additionally every node consumes E^R amount of energy to receive a packet. The initial amount of energy stored in a new node is E_0. Recall that the nodes must be replaced on or before complete energy loss. Let K be the setup cost of a replacement attempt and C be the cost of replacing a node.

Our objective is to achieve the minimum average node replacement cost in the network by joint control of routing and node replacement policies. The routing decision specifies how every node will distribute its packet transmissions to all nodes within its range. The node replacement policy or schedule specifies when to make a replacement attempt and which nodes to replace in an attempt. In order to reduce problem size and increase convenience in network operation, we assume that routing and node replacement decisions are made at the beginning of every day in the time horizon instead of every data collection round.

It is not possible to develop a tractable mathematical formulation for our problem in the given setup. Hence we modified the problem slightly and obtained an equivalent mixed integer programming (MIP) formulation (Wolsey [23]) which we subsequently prove optimal for the original problem. In the modified setup, we can replace an energy-depleted node with a new node with any amount battery of energy up to E_0. However, the cost of replacing the node is kept the same irrespective of the amount of energy stored in the new node. Note that, in the original setup of our problem, the new replacement nodes have full battery energy E_0. Now we define our decision variables below:

$r_{ij}^t =$ number of packets sent in every round from node-i to node-j in day-t,
$x^t = 1$ if a node replacement attempt is made on day-t, else 0,
$y_i^t = 1$ if node-i is replaced on day-t, else 0.

Additionally, let e_i^t denote the amount of energy remaining in node-i at the beginning of day-t (just before a possible replacement). Note that it only makes sense to replace a node with a new node with a higher amount of energy. If node-i is replaced on day-t, let w_i^t be the additional amount of energy in the incoming new node over the outgoing node (i.e. the energy stored in the new node is $e_i^t + w_i^t$). Now, in the modified setup, the optimal routing and node-replacement decisions minimizing the total replacement cost (or equivalently minimizing the replacement cost per day) can be obtained from the solution to the following MIP problem:

(MIP-1):

$$\text{Min} \quad f_1(\boldsymbol{r}, \boldsymbol{x}, \boldsymbol{y}) = K \sum_{t=1}^{T} x^t + C \sum_{t=1}^{T} \sum_{i=1}^{N} y_i^t \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in V_i} r_{ij}^t - \sum_{j \in U_i} r_{ji}^t = s_i \qquad i = 1, \cdots, N, \ t = 1, \cdots, T \tag{2}$$

$$\sum_{j \in U_{N+1}} r_{j,N+1}^t = \sum_{i=1}^{N} s_i \qquad t = 1, \cdots, T \tag{3}$$

$$e_i^1 = E_0 \qquad i = 1, \cdots, N \tag{4}$$

$$e_i^{t+1} = e_i^t + w_i^t - D \left(\sum_{j \in V_i} E_{ij}^T \, r_{ij}^t + E^R \sum_{j \in U_i} r_{ji}^t \right), i = 1, \cdots, N, \ t = 1, \cdots, T \tag{5}$$

$$e_i^t + w_i^t \leq E_0 \qquad i = 1, \cdots, N, \ t = 1, \cdots, T \tag{6}$$

$$w_i^t \leq E_0 \, y_i^t \qquad i = 1, \cdots, N, \ t = 1, \cdots, T \tag{7}$$

$$y_i^t \leq x^t \qquad i = 1, \cdots, N, \ t = 1, \cdots, T \tag{8}$$

$$r_{ij}^t \geq 0 \qquad i = 1, \cdots, N, \ j \in V_i, \ t = 1, \cdots, T \tag{9}$$

$$e_i^t \geq 0 \qquad i = 1, \cdots, N, \ t = 1, \cdots, T+1 \tag{10}$$

$$w_i^t \geq 0, \ x^t \in \{0, 1\}, \ y_i^t \in \{0, 1\} \qquad i = 1, \cdots, N, \ t = 1, \cdots, T \tag{11}$$

In the above formulation, the objective function (1) aims to minimize the total node replacement cost over the time horizon. In Equations (2)-(3), we present the packet balance conditions which must hold for any routing in the network. Equation (4) indicates that network operation is started with nodes with full battery energy. In Equation (5), we provide energy-balance conditions for each node at the beginning of each day. As per Inequality (6), the incoming new node can have stored energy up to the limit E_0. Inequality (7) stipulates the condition that the additional energy of a new replacement node can be considered only if a node replacement decision is made. As per Inequality (8), replacement of a node is possible only if a replacement attempt is made. Equations (9)-(11) specify the nature of the decision variables.

In the following proposition, we show that the solution to MIP-1 is actually the solution to our node replacement cost minimization problem in the original setup (i.e. where all new replacement nodes have full battery energy E_0).

Proposition 1: The optimal routing and node replacement decisions in MIP-1 (modified setup) are also optimal in minimizing the node replacement costs in the original setup.

Proof: Let z^* and z^{**} be the optimal total node replacement costs in MIP-1 (modified setup) and in our original problem respectively. In our original setup, new replacement nodes have full battery energy, i.e. $e_i^t + w_i^t = E_0$ whenever $y_i^t = 1$. Note that such node replacement options are also considered in the formulation MIP-1 (see Inequality (6)). In fact MIP-1 minimizes the total node replacement cost over a broader set of node replacement options than our original problem. In other words, MIP-1 is a relaxed formulation of our original problem. Hence, we have $z^* \leq z^{**}$.

Now consider the optimal solution $\{{r_{ij}^t}^*, x^{t*}, y_i^{t*}, w_i^{t*}, e_i^{t*}\}$ of MIP-1. Since replacing with a new node with any amount of energy up to E_0 costs the same amount C, we can construct an alternate optimal solution of MIP-1 (with the same objective value z^*) as $\{{r_{ij}^t}^*, x^{t*}, y_i^{t*}, w_i^{t**}, e_i^{t**}\}$ where $w_i^{t**} + e_i^{t**} = E_0$ whenever $y_i^{t*} = 1$ and the relation $e_i^{t+1**} = e_i^{t**} + w_i^{t**} - D\Big(\sum_{j\in V_i} E_{ij}^T \, {r_{ij}^t}^* + E^R \sum_{j\in U_i} {r_{ji}^t}^*\Big)$ is recursively satisfied. However, since all the new replacement nodes have full battery energy in this solution, the decision $\{{r_{ij}^t}^*, x^{t*}, y_i^{t*}\}$ is actually a feasible solution to our original problem. Therefore we have $z^* \geq z^{**}$.

Based on the above arguments, we have $z^{**} = z^*$, and $\{{r_{ij}^t}^*\}$ and $\{x^{t*}, y_i^{t*}\}$ are the optimal routing and node replacement decisions for our original problem. □

When a fixed routing decision over the entire time horizon (i.e. $r_{ij}^t = r_{ij}$ for all t) is intended in the solution of MIP-1, only one set of routing constraints (see Equations (2)-(3)) will suffice for all values of t. We will refer to this fixed routing version (of MIP-1) as MIP-2.

When a preselected fixed routing $\{r_{ij}\}$ is used in the network, the optimal node replacement schedule can be found by solving a reduced version of MIP-1 where the routing constraints given by Equations (2)-(3) are removed. However, this particular problem can be more efficiently solved in the original setup. We present this alternative formulation IP-3 in Appendix A.

Our combined routing and node replacement formulation MIP-1 as well as its simpler variant MIP-2 are intractable for a network with large number of nodes (N) and for a long deployment period (T). The difficulty is mainly due to large number of binary decision variables and the constraints given by Inequalities (7) and (8) in particular. The formulation IP-3 (in Appendix

A) is also hard to solve for sizable problem instances. Therefore, in order to minimize the node replacement costs in the underwater seismic node network that we consider in this paper, we need to develop methods that are effective and suitable for practical implementation.

III. SEISMIC NETWORK MODEL AND ASSUMPTIONS

In this section, we explain the structure of the underwater sensor network that we have considered in our model for seismic monitoring application. We also present important assumptions that are used in subsequent sections.

The area of the ocean floor covering a petroleum reservoir ranges between 50-100 *sq. km*. In ocean bottom seismic acquisition, nodes (i.e. underwater sensors) are deployed over this area usually in a square or rectangular grid [1]. For passive seismic application, the inter-node distance on this grid varies from a few hundred meters to 1 *km*. However, in the case of active seismic where collected data is primarily used for seismic imaging, nodes are placed relatively closer (usually 50-100 *m* separation) in order to improve the resolution of the seismic image. Recall that the seismic data from all the nodes must be available for analysis in real time. Hence all data from the nodes are sent to one or more sink nodes via muitihop wireless transmission. The sink node can be connected via a high-speed optical link to a node floating on the sea surface and the latter can forward the received information to the base station via a radio link. Since the size of the seismic node network and its coverage area are very large, the whole network is divided into smaller independent networks with a separate sink node for each individual network [1]. All our analyses in this paper are based on one such independent network of 120 nodes that are positioned on a square grid. Fig. 1 shows the structure of this network along with two routing strategies which we will discuss in Section IV.

Based on the network structure described above, we will now present a discussion about the transmission range which is important for the routing decision. Observe (in Fig. 1) that the nodes in our network can be thought of being arranged in concentric squares around the sink node and nodes on a particular square can be identified by a level. In our convention, the closer the square is towards the center, the lower is its level. We assume that a node in a particular level can send data to nodes within its transmission range in the next lower level. Given the noisy underwater environment and the long distance of separation between nodes, such one-hop transmission is a reliable option. For every node to have at least one other node within its range, we set the transmission range of every node at $\sqrt{2}d$ for an inter-node distance d on the grid.

Now we will briefly describe how our model and assumptions meet acoustic transmission requirements. Considering 24 *bit* per component in a standard 4-component seismic acquisition (with three geophones and one hydrophone in each node), and allowing some overhead, the output data rate per node is approximately 2 *kbps* with a 50 *ms* sampling rate. Hence we can assume that every node generates a 2 *kb* packet every second. Then it transmits its own packet and other forwarded packets to one or more nodes within its transmission range. It can be observed in the forthcoming Section IV that using uniform nodes with 50 *kbps* output capacity will safely ensure congestion-free continuous transmission with our proposed routing schemes. Note that 50 *kbps* acoustic transmission is possible with an appropriate frequency over our selected inter-node distances [24].

We will now provide mathematical expressions to calculate energy consumption at the nodes. Since most of the energy of a node is consumed in the underwater acoustic data transmission, energy consumed in sensing is negligible and we have ignored it in our model. Energy consumption in acoustic transmission depends on both distance (d) and frequency (f) of transmission. In our energy consumption model for data transmission, we have adapted the calculations to the radio transmission case (Heinzelman *et al.* [11], Kalpakis *et al.* [25]). A similar approach was briefly mentioned by Pompili *et al.* [26] for acoustic transmission. In our model, energy consumption (in *J/bit*) at a node per bit of data transfer is given by

$$\text{(For sending)} \qquad E_T(f,d) = E_{elec} + \frac{P_T(f,d)}{B} \tag{12}$$

$$\text{(For receiving)} \qquad E_R = E_{elec} \tag{13}$$

where $E_T(f,d)$ is the amount of energy to transmit 1 *bit* of data over a distance of d at frequency f in terms of $E_{elec}, P_T(f,d)$ and B which we define next. In Equation (12), the fixed component E_{elec} [*J/bit*] is the energy consumed by the electronic circuitry and $P_T(f,d)$ [*W*] is the power at which the transmitter operates specific to the frequency and the distance of transmission. The output capacity of a node for the acoustic transmission is B *bits/sec*. By Equation (13), a node will consume E_R amount of energy for receiving 1 bit of information. We have assumed a nominal value of 50 *nJ/bit* for E_{elec}. We have set the frequency (f) at 75 *kHz* for all transmissions.

We earlier explained our choice of 50 *kbps* for B. We derive an expression to compute $P_T(f, d)$ in Appendix B.

Note that, in our model, the energy consumption by a node is directly proportional to the amount of transmission it handles. However, in certain applications such as the everyday cell phones, a continuous transmission is usually worse in depleting the battery than an equal amount of transmission made over several disjoint intervals. In our application, such energy saving (based on how the transmissions are scheduled) may not be significant and hence we have not considered it in our model.

Having described the network structure and the data transmission model, now we would like to lay a foundation for operating this system with minimal node replacement cost. Recall from Section I that our application requires continuous seismic data acquisition from all node locations and hence nodes are to be replaced when they run out of battery energy. However, the sink node is externally powered and hence will not need replacement. Node replacement implies that a new battery must be provided, but in the harsh deep water environment, it is most practical to replace the entire node. In this case the node can be reused later with a new battery. We assume that the total cost in a replacement attempt is of the form $K + Cx$, where K is the fixed set-up cost of a replacement attempt, C is the cost of replacing a node and x is the number of nodes replaced in an attempt. It is assumed that the fixed cost K covers for any total distance of travel (equal to the sum of distances between the replaced nodes) on the ocean floor during a replacement attempt. The parameter C includes the cost of a new battery and cost for labor time in an individual node replacement.

IV. ROUTING AND NODE REPLACEMENT POLICIES FOR PASSIVE SEISMIC NETWORK

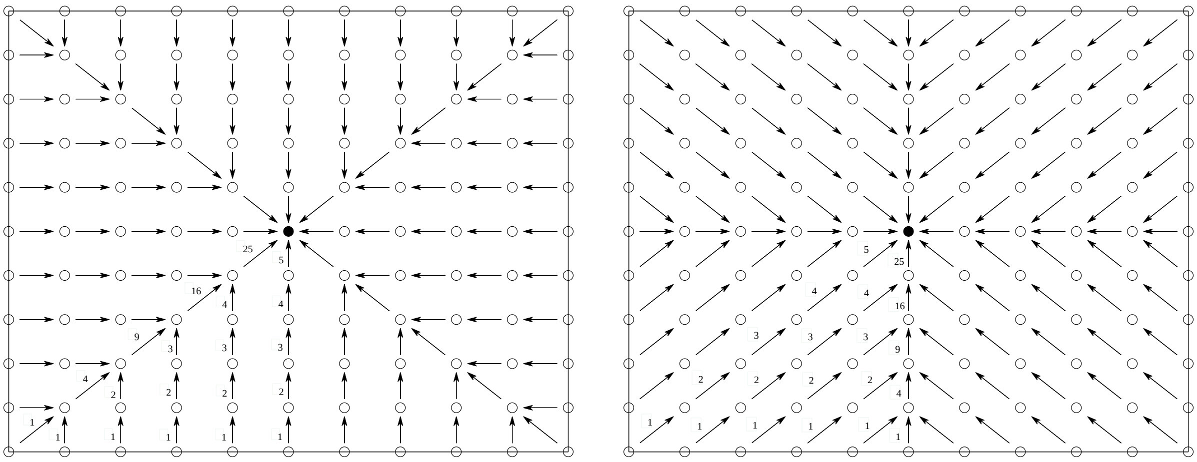
In this section, we develop effective methods to minimize the average maintenance (for node replacement) cost in a passive seismic node network. Recall from Section I that, in a passive seismic network, all nodes continuously monitor the microseismic events and send the recorded information periodically to the sink node via multi-hop wireless transfer. For this application, we consider a 120-node grid-structured network (see Fig. 1(a)) with an inter-node distance of 200 *m*.

Given the size of the considered network and its long period of operation (20-50 years), it is not possible to solve its MIP-1 formulation in order to attain the optimal average node replacement cost. Also note that the formulations MIP-2 (for fixed routing decision) and IP-3 (with a given fixed routing) are also hard to solve in this case. However we know that the node replacement cost can be effectively controlled by both routing and node replacement decisions. Based on this idea, in the following subsections, we introduce efficient routing and node replacement policies and use them in combinations to minimize the average maintenance cost of the network. To maintain consistency with earlier analysis in Section II, both routing and node replacement decisions are considered on per day basis instead of per round.

A. Routing

As we have mentioned in Section I, routing in sensor networks has been well-studied. However, given the focus on minimizing the node replacement costs in our application, we must investigate new strategies for routing packets in the network. Our aim is to minimize the number of replacement attempts as well as the total number of nodes replaced in all attempts. Hence a suitable routing scheme must have two major characteristics. First, it should have groups of large number of nodes having closest possible energy dissipation rates so that the nodes in these groups can be replaced at the same time. This will ensure a smaller number of replacement attempts. Secondly the routing should be energy-efficient in order to minimize the total number of node replacements. For our grid network, the minimum energy (also called minimum total energy (MTE) [13]) routing schemes that are symmetric about the center best satisfy these two requirements. These routings minimize the total energy consumed in all transmissions in a data collection round (which, in our case, leads to the receipt of 120 packets at the sink node and repeats every second).

In our grid network case, there are multiple minimum energy routing solutions available. From these solutions, considering symmetry around the center, we selected ME-1 (Fig. 1(a)) and ME-2 (Fig. 1(b)) routings which we describe next. In the ME-1 routing scheme, every node sends all its packets to the nearest node in its next lower level. Similarly in the ME-2 routing, most of the nodes send all their packets to the farthest node in the next lower level. The number of packets sent per round from each node in the network is shown in Fig. 1(a) and 1(b) for both



(a) ME-1

(b) ME-2

Fig. 1: Selected minimum energy routings in the network (sensing and transmitting nodes: ○, sink node: ●)

routings. In the following proposition, we present an important difference between ME-1 and ME-2 routings.

Proposition 2: When most nodes in the network have sufficient energy, ME-2 routing sustains network operation for a longer period of time than ME-1 routing till a node requires replacement.

Proof: Suppose u_i^1 and u_i^2 are energy consumption rates of the i-th ($i = 1, \cdots, N$) node in ME-1 and ME-2 routings respectively. Also, let E_i be the amount of energy remaining in node-i at a particular time. From this point, the time till next node replacement in case of ME-1 and ME-2 routings will be $T_1 := \min_i \lfloor E_i/u_i^1 \rfloor$ and $T_2 := \min_i \lfloor E_i/u_i^2 \rfloor$ respectively.

We can see (in Fig. 1) that the number of packet transmissions increases towards the center both in case of ME-1 and ME-2 routings. Hence the nodes close to the center consume energy at a faster rate than the nodes far from the center. However, an increasingly large number of packets are sent over the diagonal inter-node distance ($\sqrt{2}d$) in ME-1 routing whereas this happens over the lateral inter-node distance (d) in ME-2 routing. Hence we have $\max_i u_i^1 > \max_i u_i^2$. Hence, when E_i's are sufficient, we have $T_1 < T_2$. □

Now, by running a combination of ME-1 and ME-2 routings (while keeping the total energy consumption in a round still minimum), we can significantly increase the network survivability further. For such a hybrid routing which we will call ME-H, the optimal combination of ME-1 and ME-2 routings can be found from the solution to the following integer programming problem:

$$\text{(IP-4):}\quad \text{Max} \quad X_1 + X_2 \tag{14}$$

$$\text{s.t.} \quad u_i^1 X_1 + u_i^2 X_2 \leq E_i \qquad i = 1, \cdots, N \tag{15}$$

$$X_1, X_2 \geq 0, \text{integer} \tag{16}$$

where u_i^1 and u_i^2 are the per-day energy consumption rates of node-i in ME-1 and ME-2 routings respectively, E_i the amount of energy in node-i at the time of consideration, and X_1 and X_2 are the number of days for which the ME-1 and ME-2 routings will be run respectively. We will use these energy-efficient ME-1, ME-2 and ME-H routings for all our models in subsequent sections.

B. Node Replacement Policy

A node replacement policy for our problem is a rule to decide when to make a replacement attempt and which nodes to replace in an attempt. Recall from Section I that the economies of scale in the replacement cost model lead to cost savings when several nodes are replaced together in a replacement attempt. So, while replacing the completely energy-exhausted nodes, it will be cost-effective to replace some additional nodes that have low residual energy. Hence a node replacement policy for our problem will essentially try to use this preventive replacement option to an optimal degree to minimize the average maintenance cost.

Note that the formulations MIP-1, MIP-2 and IP-3 do allow preventive node replacement when it is optimal to do so. However, besides the known intractability of these formulations for sizable problem instances, the possible optimal replacement schedules in these cases may be highly irregular and hence are not suitable for practical implementation. In fact we require replacement policies to be fixed, simple and easy to implement. Based on these considerations, we propose the following three replacement policies to decide when to make replacement attempts and which nodes replace in every attempt.

1) *Fixed Interval Replacement (FI):* Here the time interval between replacement attempts is fixed. If we fix this interval as F days, a replacement attempt can be made on days

numbered kF (for $k = 1, 2, \cdots$). On any replacement attempt, all nodes that will not survive till the next possible attempt will be replaced. Also, a replacement attempt will not be made if all nodes are known to survive till the next possible attempt.

2) *Fixed Residual Energy - Percentage based Replacement (FRP):* With this policy, a replacement attempt is made only when a node fails and all nodes with residual energy less than a fixed threshold level are replaced. Here we specify this energy threshold as a percentage ($p\%$) of initial battery energy E_0.
3) *Fixed Residual Energy - Day based Replacement (FRD):* This policy is similar to FRP. In this case, a replacement attempt is made only when a node fails and all nodes with residual energy not sufficient to survive for at least another F_{FRD} (fixed) number of days are replaced. Note that the residual energy threshold here is the amount of energy just sufficient for F_{FRD} number of days.

In each of above policies, either the decision for a replacement attempt or the decision on individual node replacement is based on a simple fixed strategy. Note that both FRP and FRD are threshold-based replacement policies. However, unlike FRP, the residual energy threshold levels in FRD are different for nodes with different energy consumption rates. Also, the main difference between FI and FRD replacement policies is in the decision on when to make a replacement attempt.

C. Combining Routing and Node Replacement Policies

Now we will describe how our proposed replacement policies (FI, FRP and FRD) can be used with ME-1, ME-2 and ME-H routings. It can be observed from the definitions of FI, FRP and FRD policies that they are easily implementable with a fixed routing such as ME-1 and ME-2. When a fixed routing is used, any replacement schedule over a time period of T days is a feasible solution to the problem IP-3 (given in Appendix A). Hence for ME-1 and ME-2 routings, the replacement schedules given by FI, FRP or FRD policies will not be any better than the IP-3 solution schedule. However, we seek to answer the question how good they are. In fact these schedules, unlike the IP-3 solution, are easy to find and they always have some regularity associated with them.

The ME-H routing is easy to use only with the FRP replacement policy. When it is used with the FI or FRD policy, it is not clear which nodes to replace in a replacement attempt. This is because X_1 and X_2 values (following a replacement) are not known at the time of replacement and hence the knowledge of whether a node will last for additional F (F_{FRD} for FRD policy) number of days is not available at that time. Recall that X_1 and X_2 are the number of days for which the ME-1 and ME-2 routings will be run respectively. We propose the following integer programming model that helps decide which nodes to replace in a replacement attempt in case of ME-H routing with FI policy (use F_{FRD} in place of F for FRD policy):

$$
\begin{aligned}
\text{(IP-5): Min} \quad & f_5(\boldsymbol{y}) = \sum_{i=1}^{N} y_i && && (17)\\
\text{s.t.} \quad & u_i^1 X_1 + u_i^2 X_2 \le E_i(1-y_i) + E_0\, y_i && i = 1, \cdots, N && (18)\\
& X_1 + X_2 \ge F && && (19)\\
& X_1, X_2 \ge 0, \text{integer} && && (20)\\
& y_i \in \{0,1\} && i = 1, \cdots, N. && (21)
\end{aligned}
$$

where y_i is the decision whether or not to replace the i-th node. All other parameters and variables remain the same as those defined for the formulation IP-4 (given by Equations (14)-(16)). The objective function given in Expression (17) aims to minimize the number of nodes that are to be replaced in the current attempt. Inequality (18) provides the constraint on the available energy for each node (E_0 if the node would be replaced, else E_i). Inequality (19) specifies that the next replacement attempt is no sooner than F days. As an alternative to solving the formulation IP-5 to find the replacement decision in FI policy, we can use a relaxed approach where we will replace the i-th node in a replacement attempt if $E_i < F\ \max\{u_i^1, u_i^2\}$ (use F_{FRD} in place of F for FRD policy). This ensures that none of the nodes will run out of energy in the next F days for any combination of X_1 and X_2. However, this may lead to preventive replacement of a few additional nodes.

We can now use our proposed node replacement policies when any of the ME-1, ME-2 and ME-H routing is used for packet transmission in the network. Since all these combined policies are intractable to study analytically for the network of our size, we take a numerical approach to study their properties. We provide detailed numerical results in the following section.

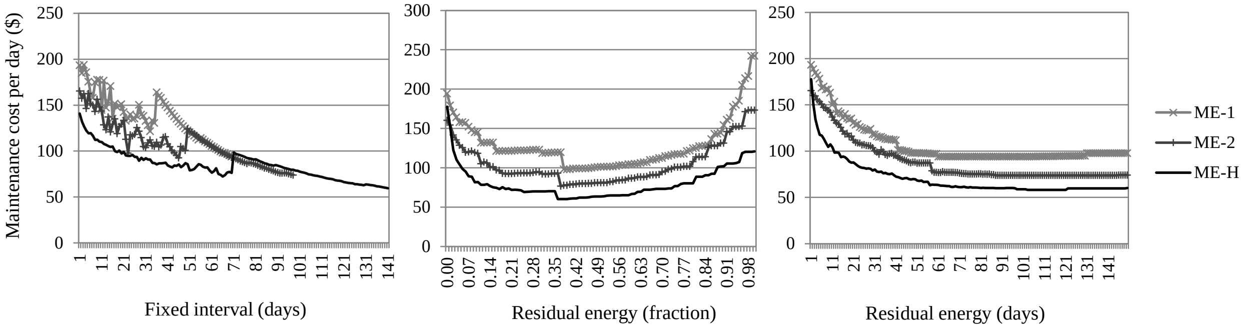
V. NUMERICAL RESULTS

We implemented the proposed routing and node replacement policy combinations on the grid-structured passive seismic network with an inter-node distance of 200 m. Most of the results that we discuss in this section are based on our MATLAB simulations of the given network operation for a time period $T = 50$ years. All MIP/ IP formulations are solved using the CPLEX 12 solver. The initial battery energy of a new node is taken as $E_0 = 50000\ J$ which is close to the amount of energy stored in a MEMS-based compact node currently used in seismic monitoring [7]. Considering the cost of this battery and the labor cost associated with the node replacement in deep underwater conditions, the cost of an individual node replacement is approximately estimated as $C = \$100$. Since the fixed cost of a replacement attempt K is unknown and difficult to estimate, we consider three different cases: K =\$1000, \$5000 and \$15000. While $K = \$5000$ is a close practical possibility, lower and higher values of K are considered to verify that our approach is still effective for all other values of K.

It is important to see how different routings perform with a particular replacement policy over the range of its fixed parameter (i.e. F in FI, F_{FRD} in FRD and p in FRP). Fig. 2 shows such performance comparisons in terms of average maintenance cost of the node network for $K = \$5000$. The results for the cases $K = \$1000$ and $K = \$15000$ are found very similar to those for the case $K = \$5000$ and hence are not shown.

Fig. 2(a) shows how the average maintenance cost changes when we change the replacement interval (F days) in the FI replacement policy. In ME-1 routing, the four nodes at the corners of the lowest level square (see Fig. 1(a)) have the fastest energy consumption rate and they exhaust full battery energy in 70 days. This primarily means that the maximum possible interval in the FI policy for ME-1 routing is 70 days. Similarly in ME-2 and ME-H routings, only the fastest energy consuming nodes impact the range of F. It can be observed that ME-H routing achieves the lowest average cost among all routings for FI replacement policy. The sharp jumps right after the mid-point of the maximum possible interval can be attributed to the fact that more number of nodes with high residual energy are to be replaced for those values of F.

Fig. 2(b) shows the variations in the average maintenance cost when the threshold energy level (in terms of percentage parameter p) is changed in FRP replacement policy. As expected,

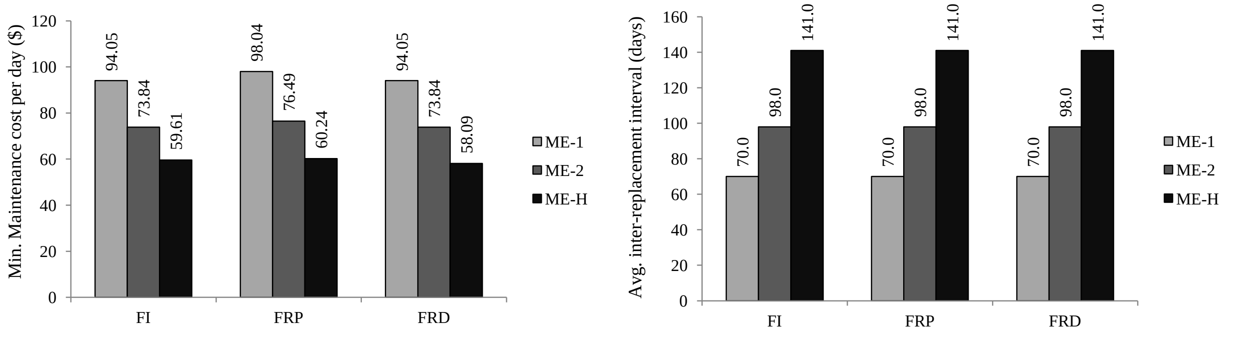


(a) FI (b) FRP (c) FRD

Fig. 2: Average maintenance cost ($E_0 = 50000$ J, $K = \$5000$, $C = \$100$ and $T = 50$ years)

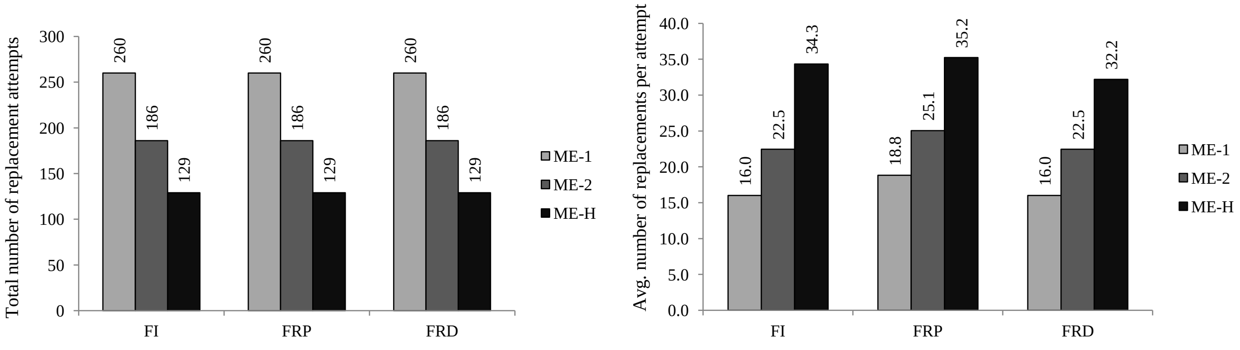
with the increase in p value, the average cost first decreases and then increases. The average maintenance cost in FRD policy follows a similar trend (see Fig. 2(c)) as we change the fixed parameter F_{FRD}. Based on our argument in the FI policy case, it does not make sense to increase the value of the fixed parameter F_{FRD} in FRD policy beyond the corresponding maximum F values in FI policy for each routing. For example, in the ME-1 routing case, we must make a replacement attempt at least once in every 70 days. Though it is possible to take value of F more than 70 days for this routing with FRD replacement policy, we can see in the plot that the average cost only increases beyond this value of F_{FRD}.

Our idea is ultimately to use the value of the fixed parameter (in the node replacement policy) with which a routing attains the minimum average maintenance cost. We present in Fig. 3(a) a comparison of the minimum average maintenance costs obtained from all combinations of our proposed routings and replacement policies for the case $K = \$5000$. We have shown that the lowest average maintenance cost is achieved with the ME-H routing in every replacement policy. The ME-2 routing provides a lower average cost than ME-1 routing in most cases, but the ME-H routing is significantly better than both ME-1 and ME-2 routings in all cases. These observations are consistent with our discussions related to network survivability in Section IV.A. Since the fixed cost of a replacement attempt (K) is very high compared to the individual node replacement cost (C), the minimum energy routing that achieves a higher degree of network survivability is also expected to produce a lower average node replacement cost. It can also be observed that FRD replacement policy results in a lower average maintenance cost than FI and



(a) Minimum average maintenance cost

(b) Inter-replacement interval



(c) Number of replacement attempts

(d) Node replacements per attempt

Fig. 3: Performance comparison of policy combinations ($E_0 = 50000$ J, $K = \$5000$, $C = \$100$ and $T = 50$ years)

FRP policies when a particular routing is kept fixed. Again FI does better than FRP and is close to FRD in minimizing the average replacement cost.

In addition to providing the minimum average maintenance cost, a replacement policy (or schedule) may be required to meet certain service-level criteria. In Fig. 3(b)-3(d), we present the performance comparison of our proposed policies in terms of important service level parameters for $K = \$5000$. The node replacement service will require minimum number of replacement attempts over the period of operation. The inter-replacement interval is also desired to be as long as possible. It can be observed that, in case of most replacement policies, ME-2 routing results in less number of replacement attempts compared to ME-1 routing, but ME-H routing achieves the lowest number of replacement attempts. The ME-H routing also achieves a longer inter-replacement interval with all replacement policies. The observations in Fig. 3(a)-3(d) are similar for the cases $K = \$1000$ and $K = \$15000$ and hence are not shown.

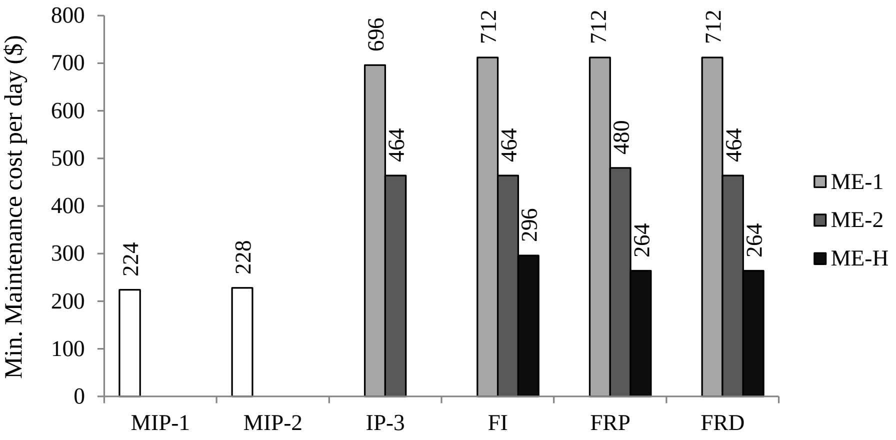


Fig. 4: Minimum average maintenance cost ($E_0 = 5000$ *J*, $K = \$5000$, $C = \$100$ and $T = 25$ days)

As we know, though the formulation MIP-1 is optimal in minimizing the node replacement cost, this approach can be employed when the number of nodes in the network (N) and the time horizon (T) are small. However, in order to compare the results of our proposed methods with this optimal solution case, we repeated our experiments for time horizon $T = 25$ days. This was one of the largest instances for which we could solve MIP-1 to optimality within 30 minutes. Also, in order to ensure a good number of node replacements during this small period of operation, we considered initial battery energy $E_0 = 5000$ *J*. For this network setup with $K = \$5000$ and $C = \$100$, we present in Fig. 4 a comparison of minimum average maintenance costs achieved by different approaches that we have considered in this paper. As expected, MIP-1 solution provides the lowest average maintenance cost among all approaches considered. As MIP-2 approach considers only fixed routing decisions, the minimum average maintenance cost increases in this case over the MIP-1 solution. When a given fixed routing (e.g. ME-1 and ME-2) is used in the network, IP-3 based solution provides the best results. Also, observe that ME-H routing when used in combination with our proposed node replacement policies provides a minimum average maintenance cost that is close to the optimal MIP-1 case. Though this cost gap may look to be considerable in the presented scenario (in Fig. 4), this will significantly improve when large values would be considered for the time horizon (T).

We also applied our methods to minimize node replacement costs in an integrated active-passive seismic application. Here passive seismic monitoring is done continuously and active seismic surveys are conducted once in every few months. Due to closer inter-node spacing requirement for active seismic, we considered a 50 *m* separation between nodes on our grid network. Note that this network with the reduced inter-node distance is also suitable for passive seismic. The results for this special case are similar to the passive seismic application and hence are not separately presented.

VI. CONCLUSIONS

In this paper, we developed methods to minimize node replacement costs in underwater wireless sensor networks used in seismic monitoring of undersea oilfields. We introduced the combined routing and node replacement approach to minimize the replacement costs, and developed mathematical formulations that provide the optimal solution. However these MIP/IP formulations become intractable for sizable networks with prolonged seismic monitoring operation. Hence we introduced effective routing and node replacement policies and used them in combinations to achieve the minimum average node replacement cost.

As our numerical results indicate, the ME-H routing with FI or FRD replacement policy provides significantly lower average node replacement cost and meets higher service-level requirements than other joint policies. Though the use of FRD replacement policy with ME-H routing provides the best results, FI policy can still be preferred given its higher degree of simplicity. Also, the difference in the performances of the considered minimum-energy routings ME-1, ME-2 and ME-H is attributed to the varied degree of energy-balancing they achieve. Among the proposed node replacement policies, though the threshold-based FRD policy performs as good as expected, the results also show that using the simple policies like FI in this application is not a bad idea at all. Overall, the main result of this paper shows that the combined routing and node replacement policy approach is effective and suitable for practical implementation. This approach will also apply to similar permanent monitoring applications that use remotely located large sensor networks.

We envision many interesting extensions of this work for future research. As an immediate extension, effective methods can be developed to minimize node replacement costs in a generic sensor network. It would also be interesting to see how our methods can be applied to networks that can work with a certain percentage of failed nodes. Additional re-routing routines will be required in this case. The nature of our problem is analogous to a multicomponent maintenance model where the components have both structural and economic dependence. New replacement policies can also be explored in this area.

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APPENDIX A

OPTIMAL NODE REPLACEMENT SCHEDULE FOR A GIVEN FIXED ROUTING

Under a given fixed routing $\{r_{ij}\}$, the lifespan (in days) of node-i is estimated as $L_i = \left\lfloor E_0 / \left(D \left\{ \sum_{j \in V_i} E^T_{ij}\, r_{ij} + E^R \sum_{j \in U_i} r_{ji} \right\} \right) \right\rfloor$. All the notations used here are defined in Section II. Now the node replacement schedule minimizing the total replacement cost (or equivalently minimizing the replacement cost per day) can be obtained from the solution to the following integer programming problem:

$$\text{(IP-3): Min} \quad f_3(\boldsymbol{x}, \boldsymbol{y}) = K \sum_{t=2}^{T} x^t + C \sum_{t=2}^{T} \sum_{i=1}^{N} y_i^t \tag{22}$$

$$\text{s.t.} \quad y_i^t \le x^t \qquad i = 1, \cdots, N,\ t = 1, \cdots, T \tag{23}$$

$$y_i^1 = 1 \qquad i = 1, \cdots, N \tag{24}$$

$$\sum_{t=k}^{k+L_i-1} y_i^t \ge 1 \qquad i = 1, \cdots, N,\ k = 1, \cdots, (T - L_i + 1) \tag{25}$$

$$x^t, y_i^t \in \{0, 1\} \qquad i = 1, \cdots, N,\ t = 1, \cdots, T, \tag{26}$$

where x^t and y_i^t are node replacement decisions at the beginning of a day for a replacement attempt and an individual node replacement respectively. Inequality (23) specifies that a node can be replaced only when a replacement attempt is made. Equation (24) indicates that network operation is started with nodes with full battery energy. However, note that using new nodes at beginning is not actually node replacement and hence its cost is ignored in the objective function (22). As per Inequality (25), the i-th node must be replaced at least once in any span of L_i days. This ensures that every node is replaced on or before complete energy loss.

APPENDIX B

EXPRESSION FOR $P_T(f, d)$

We will use some of the available results to find an expression for $P_T(f, d)$ specific to our model. The passive sonar equation describing major energy losses (given by signal-to-noise ratio SNR) in an acoustic transmission is given as (Urick [27]):

$$SNR = SL - TL - NL + DI \tag{27}$$

where SL is the source level, TL is the transmission loss, NL is the noise level and DI is the directivity index. All quantities in Equation (27) are in *dB re μPa*, where the reference pressure of 1 *μPa* corresponds to the reference intensity 0.67×10^{-18} *W/m*^{2}. Assuming ambient noise level NL of 70 *dB*, a target SNR of 20 *dB* at the receiver and not considering directivity effect, we will have a required source level $SL = TL + 90$ *dB*.

The transmission loss TL has a highly non-linear relationship with distance and frequency. Its expression involving major path loss components is given as [27]:

$$TL = 10 \log d^2 + d \times 10^{-3} \times 10 \log \alpha(f) \tag{28}$$

where the first term in the summation represents spreading loss and the second term represents absorption loss. These losses are explained in greater detail by Lanbo *et al.* [28], Stojanovic [29] and Urick [27]. We have assumed spherical spreading considering that the nodes are mounted at deep underwater locations. In fact this spreading factor in practice would be tuned based on measurements. In Equation (28), $\alpha(f)$ is the absorption coefficient and it is expressed in dB/km for frequency f [*kHz*] by Thorp's formula (Brekhovskikh and Lysanov [30]):

$$10 \log \alpha(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003.$$

Now we will use the estimate of $SL = TL + 90$ to find an expression for the required transmission power $P_T(f, d)$. The source level SL is defined as the intensity I at a reference point located at a distance of 1 *yard* (0.9144 *m*) from the acoustic center of the source, relative to the reference intensity $I_{ref} = 0.67 \times 10^{-18}$ *W/m*^{2} in underwater acoustics [27].

$$SL = 10 \log \frac{I}{I_{ref}}.$$

If SL is targeted to achieve the required SNR at a distance d, the transmitter power required to produce the intensity I at the reference point is also the minimum power required to transmit up to distance d. Hence, for a given frequency f, we can find the transmitter power $[W]$ as:

$$P_T(f,d) = 0.67 \times 10^{-18} \cdot 4\pi(0.9144)^2 \cdot 10^{\frac{(10 \log d^2 + d \times 10^{-3} \times 10 \log \alpha(f)) + 90}{10}}.$$

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