

# An Integral Flow-Based Energy-Efficient Routing Algorithm for Wireless Sensor Networks

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*Abstract*—Sensor networks consist of a large number of sensor nodes performing distributed sensing and event detection. As sensor nodes are energy-constrained, energy-efficient routing is essential for increasing the lifetime of a sensor network. In [15] we proposed an ILP-based method for routing in sensor networks with multiple mobile base stations. The ILP-based method does not guarantee integral routes and bounds on running time. In this paper, we consider static base stations and propose an algorithmic approach to obtain integral energy-efficient routes.

We propose to split the lifetime of a sensor network into equal periods of time referred to as rounds and model the energy constrained routing during a round as polynomial-time solvable flow problems. The flow information from an optimum solution to a flow problem is then used as a basis for an energy-efficient routing protocol. Through simulations, we demonstrate that our routing algorithm performs significantly better than the shortest path based algorithms and consumes less energy than the ILP-based method. In addition, we present an algorithm to determine, a priori, lower bound on the lifetime of the sensor network.

**Keywords:** Wireless Sensor Networks, Routing.

## I. INTRODUCTION

Micro sensing devices, each equipped with a low computational capacity processor and a wireless transmitter-receiver, referred to as sensor nodes, are the building blocks of a sensor network. Sensor nodes are envisioned for on-the-fly deployment and unattended mode of operation [3], [5], [7], [11], [14]. They are expected to perform distributed sensing and report the detected events to a set of base stations associated with the sensor network.

Each sensor node is powered by limited battery-supplied energy. As sensor nodes can be deployed in very large numbers at remote locations, it is typically not feasible to recharge their batteries. Once a node depletes its energy, it is considered dead (i.e. unable to transmit or relay any messages). Thus, to increase the lifetime of a sensor network, it is essential to design energy-efficient protocols that enable sensor nodes to communicate with one or more base stations.

In [15], we proposed an Integer Linear Program (ILP) based method for energy-efficient routing in sensor networks with multiple mobile base stations. The base station locations and routing information was re-calculated at the beginning of each round. This method can be easily adapted for static base stations; however, the flow information obtained (and used for routing) on solving the ILP is not guaranteed to be integral (because the flow variables are defined to be linear). As it is

not advisable to split the packets (due to overhead), integral flow values are highly desirable. The solution offered in [15] was to round the non-integral flow values by using a sub-optimal rounding procedure. Moreover, we cannot guarantee any bound on running time of the ILP-based method.

The method proposed in this paper results in integral flow values and therefore the flow information can be used without any rounding in a routing protocol. Our routing algorithm is based on modeling the routing problem during a round as well-known polynomial-time solvable network flow problems [13]. The solution to a flow problem specifies the flow on each wireless link of the sensor network. We exploit these flow values to route packets from sensor nodes to base stations. We consider two objectives: (1) minimizing the total energy spent in a round and (2) minimizing the maximum energy spent by any node in a round. Note that the solution for second objective function need not be unique. An improvement we propose for the second objective function is to determine the minimum cost solution among all the solutions.

## II. RELEVANT WORK

Routing in sensor networks has received the attention of many researchers. The protocols proposed in the literature can be broadly classified as (1) cluster-based routing and (2) flat routing protocols. In cluster-based protocols, some elected cluster-heads discover and maintain the routing information; in flat routing, all the nodes in the network participate in route discovery and maintenance. Most of the cluster-based routing protocols [2], [16] propose to transmit data from the cluster head to the base station directly. It is well known [6] that the energy spent in transmission over a wireless medium is directly proportional to  $d^c$ , where  $d$  is the transmission range and  $c$  is a constant between 2 to 4. Moreover, in [15], it is shown through simulation results that increasing the transmission range beyond certain value decreases the lifetime of the sensor network. Thus, cluster-based protocols are typically not scalable to large-scale sensor networks. Therefore we concentrate on development of flat routing protocols.

In [4], the authors proposed Minimum Cost Forwarding (MCF) approach for routing in sensor networks. MCF finds shortest paths from all the sensor nodes to the base station and requires no explicit routing tables to be maintained at each node. Routing all the data along a shortest path might potentially drain all the energy from upstream nodes, thus

losing coverage in some regions of the network. In our method, we mitigate this possibility by limiting the amount of energy each node can spend in a round.

C-SPEAR [9] is a cluster-based protocol employing flat routing within a cluster. C-SPEAR assumes that cluster-heads are less energy-constrained and are aware of the exact location of the sensor nodes in their respective clusters. Cluster-heads determine the best transmission range for each node and employ a shortest path based scheme to determine the routes. C-SPEAR considers re-routing only when the energy level of a node drops below a threshold. Our approach does not require base stations to know the location of sensor nodes and attempts a balanced dissipation of energy across all nodes throughout the lifetime of the network.

The rest of the paper is organized as follows. Section III describes the system model. Problem formulation is presented in section IV. The solution approach is described in section V. Section VI describes a flow-based routing protocol. Section VII addresses the implementation issues. Simulation results and the algorithm to determine the lifetime of the sensor network are presented in section VIII. Concluding remarks and future work directions are provided in section IX.

### III. SYSTEM MODEL

We make the following assumptions about the network:

- 1) Each sensor node has a unique pre-configured id, fixed transmission range and the same amount of initial energy.
- 2) The sensor network is proactive [2] and each node generates equal amount of data per unit time. Each data unit (packet) is of the same length.
- 3) The transceiver exhibits first order radio model characteristics [16], where energy dissipation for the transmitter or receiver circuitry is constant per bit communicated. In addition, we assume that energy spent in transmitting a bit over a distance  $d$  is proportional to  $d^2$ . In [6], the transmission energy was assumed to be proportional to  $d^4$ . The main conclusions of our work remain valid for this assumption as well.
- 4) There exists a contention-free MAC protocol (e.g. SMACS [8]) that provides channel access to the nodes.
- 5) There exists a multi-hop routing protocol for bootstrapping our routing algorithm. For example, the Minimum Cost Forwarding (MCF) protocol [4] can be used.
- 6) One or more base station(s) are associated with the network.
- 7) We consider equal periods of time called *rounds*. At the beginning of each round, routing information is recalculated to account for changes in the topology.

### IV. PROBLEM FORMULATION

Now, we formally define the routing problem. Let the sensor network be represented as a graph  $G(V, E)$  where

- 1)  $V = V_s \cup V_b$  where  $V_s$  is the set of sensor nodes and  $V_b$  is the set of base station(s).
- 2)  $E \subseteq V \times V$  represents the set of wireless links.

Let a round consist of  $T$  time frames. Each sensor node generates one packet of data in every time frame. At the beginning of a round, let a sensor node  $i$  have residual energy  $RE_i$ . During a round, the total energy spent by sensor node  $i$  can be at most  $\alpha \times RE_i$ , where  $\alpha$  ( $0 < \alpha \leq 1$ ) is a parameter. We consider the following two objectives:

- 1) Minimize the total energy spent by all nodes in the round. We refer to this problem as the Minimum Cost Routing (MCR) problem.
- 2) Minimize the total energy spent in the network such that the maximum energy spent by a node in a round is minimized. We refer to this problem as Min-MINMAX.

It is known that the energy spent by a node is directly proportional to the amount of flow passing through the node. Thus, minimizing the maximum energy spent by a node is same as minimizing the maximum flow through a node. Hence, we consider the problem of minimizing the maximum flow through the node (referred to as MINMAX) and then determine the minimum cost MINMAX (Min-MINMAX) solution. MINMAX attempts to balance the energy spent by all the nodes, thus prolonging lifetime of the sensor network. Next, we describe how to abstract MCR (resp. MINMAX) as a Minimum Cost Flow Problem (resp. Maximum Flow problem) [13] and obtain an optimal integral solution.

### V. ROUTING AS FLOW PROBLEMS

Both the Maximum Flow problem and the Minimum Cost Flow problem are fundamental and well-studied network flow optimization models. We refer the reader to [13] for a thorough discussion of properties and algorithms for these problems.

#### A. MCR as a minimum cost flow problem

In the minimum cost flow problem, given a directed graph  $G(V, E)$ , supply/demand at node  $i$  represented by  $b(i)$ , cost  $c_{ij}$  and capacity  $u_{ij}$  of each link  $(i, j) \in E$ . We need to determine the flow  $x_{ij}$  on each arc  $(i, j) \in E$  such that supply/demand at each node and capacity constraint of each link are satisfied. In addition, the total cost of the flow given by  $\sum_{(i,j) \in E} c_{ij} x_{ij}$  is to be minimized. We abstract the MCR problem as a minimum cost flow problem as follows:

- 1) Replace each undirected link  $(i, j) \in E$  with two directed links  $(i, j)$  and  $(j, i)$ . These links will be uncapacitated and will have a cost  $C_t$  associated with them (see Figure 1). Here,  $C_t$  is the energy spent in transmitting a packet.
- 2) Split each node  $i \in V_s$  (set of sensor nodes) in the network into two nodes  $i^0$  and  $i^1$ . Add the directed link  $(i^0, i^1)$ . All the incoming links of node  $i$  will be incident on  $i^0$  and the outgoing links will be incident from  $i^1$  (see Figure 1). Node  $i^1$  will be a source node with an excess flow of  $T$  (number of time frames in a round) units.
- 3) Assign the capacity of each link  $(i^0, i^1)$ , corresponding to a node  $i$ , as  $\max(0, \lfloor \frac{(\alpha \times RE_i) - (C_t \times T)}{C_r + C_t} \rfloor)$ . Here,  $C_r$  and  $C_t$  represent the cost of receiving and the cost of

transmitting a packet respectively <sup>1</sup>. Assign a cost of  $C_r$  to links  $(i^0, i^1)$  corresponding  $\forall i \in V_s$ .

- 4) Add a sink node  $S_d$  and links  $(j, S_d)$  for all  $j \in V_b$  (set of base stations). Let the deficit flow at node  $S_d$  be equal to  $|V| \times T$ .

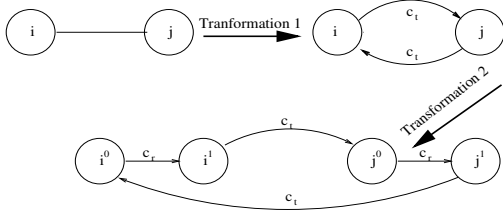


Fig. 1. Transformations for MCR

For  $i \in V_s$ , transformation (1) accounts for the energy spent in transmitting a packet by node  $i$ . The energy spent in receiving a packet by node  $i$  is accounted by transformation (3). Proofs of correctness of transformations (1) and (2) can be found in [13]. The expression given in transformation (3) converts the energy that a node can spend in a round ( $\alpha \times RE_i$ ) to an equivalent number of packets that a node can forward during that round. In this expression,  $C_t \times T$  represents the energy required in a round by node  $i$  to transmit packets that originate at that node.  $(\alpha \times RE_i - C_t \times T)$  is the amount of energy that node  $i$  can spend in a round to forward packets originating at other nodes. Thus,  $\max(0, \lfloor \frac{(\alpha \times RE_i) - (C_t \times T)}{C_r + C_t} \rfloor)$  gives the number of packets (originating at other nodes) that node  $i$  can forward in a round.

The fastest known algorithm for solving the minimum cost flow problem has a running time of  $O((|E| \log |V|)(|E| + |V| \log |V|))$  [10], [13]. Furthermore, if the supply/demand and all link capacities are integers, the minimum cost flow problem always has an integral optimum solution (i.e. the flows on all the links are integral) [13]. The integrality property is especially desirable for routing purposes.

### B. MINMAX as a maximum flow problem

In the maximum flow problem [13], given a directed graph  $G(V, E)$ , supply node  $S_s$  and demand node  $S_d$  and capacity  $u_{ij}$  of each link  $(i, j) \in E$ . We need to determine the flow  $x_{ij}$  on each arc  $(i, j) \in E$  such that the net outflow from the supply node is maximized. The MINMAX problem can be solved by abstracting it as a maximum flow problem as follows:

- 1) Perform the transformations described above (for MCR). Set the cost of all links to zero. Ignore the surplus/deficit flow of each node.
- 2) Add a new node  $S_s$  (source node) and links  $(S_s, i^1)$  for all  $i \in V_s$ . Let the capacity of such links be  $T$ .
- 3) Solve the resulting maximum flow problem. Among the links  $(i^0, i^1)$ , corresponding to each sensor node  $i$ , determine the link which has maximum flow on it. Let  $X_{max}$  be the flow on this link.

<sup>1</sup> $C_r$  and  $C_t$  can be determined from the transceiver specifications.

- 1)  $min_{cap} = 0$ ;
- 2)  $max_{cap} = X_{max}$ ;
- 3)  $current_{cap} = \lfloor \frac{min_{cap} + max_{cap}}{2} \rfloor$ ;
- 4)  $u_{ij} = \lfloor \min(u_{ij}, current_{cap}) \rfloor \quad \forall (i, j) \in E$ ;
- 5) **if** ( $min_{cap} \geq max_{cap}$ )  
    **return**;
- 6) Solve the new maximum flow problem.  
    Let  $max_{flow}$  be the maximum flow value.
- 7) **if** ( $max_{flow} == |V| \times T$ )  
     $max_{cap} = current_{cap}$ ;  
    **GOTO** (3);  
    **else**  $min_{cap} = current_{cap}$ ;  
    **GOTO** (3);

Fig. 2. Binary Search for MINMAX

- 4) The optimum solution value of MINMAX would be less than  $X_{max}$ . Hence we perform a binary search, as shown in Figure 2, to obtain the minimum value of  $X_{max}$  for which the corresponding maximum flow is  $|V| \times T$ .

The maximum flow problem, being a special case of the minimum cost flow problem, also satisfies the integrality property. By using excess scaling algorithm [12] maximum flow problem can be solved in  $O(|V||E| + |V|^2 \log U)$  time. Thus the MINMAX problem can be solved in  $O(|V||E| \log U + (|V| \log U)^2)$  time (because binary search takes  $\log U$  iterations), where  $U$  is the maximum capacity of any edge in the graph. From transformation (3) of MCR, we know that value of  $U$  is directly proportional to  $RE_{max}$  ( $= \max_{i \in V_s} RE_i$ ). Thus MINMAX can be solved in  $O(|V||E| \log RE_{max} + (|V| \log RE_{max})^2)$  time.

### C. Solving Min-MINMAX

As stated earlier, an improvement over MINMAX would be Min-MINMAX. Here, the objective is to determine the minimum cost MINMAX solution. After solving the MINMAX problem we can obtain the solution of Min-MINMAX problem by formulating a minimum cost problem as follows:

- 1) Perform all the transformations described for MCR.
- 2) For each link  $(i^0, i^1)$ , corresponding to node  $i$ , assign the link capacity  $u_{i^0 i^1} = \sum_{j \in N_i} x_{ij} - T$ . Here,  $x_{ij}$  is the flow on link  $(i, j)$  in the MINMAX solution and  $N_i$  represents the neighbors of node  $i$ .
- 3) Solve the resulting minimum cost flow problem to obtain the solution for Min-MINMAX.

## VI. FLOW BASED ROUTING PROTOCOL

On solving the MCR or the Min-MINMAX problem, we obtain the flow on individual links. This individual link flow information can be used to route the messages in an energy-efficient manner. A routing protocol using flow information is described in [15]. Here, we describe the flow-based algorithm for the sake of completeness. Once a sensor node has the flow information it would perform routing as described below.

- (i) At each node, for every outgoing link  $(i, j)$  a counter is maintained. The value of the counter is set to the outgoing flow ( $x_{ij}$ ) on that particular link.
- (ii) Whenever a node needs to transmit packets, it would select one of the outgoing links in a round robin fashion.

- 1) Use MCF [4] routing protocol in the first round.
- 2) Collect neighborhood information of all the sensor nodes and construct the topology of the sensor network.
- 3) Set value of  $\alpha = 0.01$ .
- 4) Formulate Min-MINMAX (MCR) Problem.
- 5) **If** the problem is feasible **GOTO** step (8).
- 6) **Else if** ( $\alpha == 1$ ) declare sensor network as dead.
- 7) **Else**  $\alpha = \alpha + 0.01$  and **GOTO** step (4).
- 8) At the beginning of next round, update nodes with new routing information.
- 9) Predict the residual energy values of nodes at the end of the current round.
- 10) **GOTO** step (4).

Fig. 3. An Overview of Min-MINMAX (MCR) Routing

- (iii) If the counter value of the selected link is greater than the number of packets that have to be transmitted, then all the packets are transmitted on that link and counter value is decremented by the number of packets transmitted; otherwise the number of packets equal to the counter value of the link are transmitted along the link and its counter value is set to 0. To transmit the remaining messages, outgoing links with non-zero counter values are selected in a round robin fashion.

## VII. IMPLEMENTATION DETAILS

To implement the above described flow-based routing, we need to address the following issues:

- A. Gathering topology information.
- B. Tracking residual energy of nodes.
- C. Solving MCR and Min-MINMAX.
- D. Updating routing information of all the nodes.

In the very first round, network topology required to formulate either MCR or Min-MINMAX is not available. As proposed in [15], we can employ a modified Minimum Cost Forwarding (MCF) routing protocol [4] in the first round. During the first round each node will transmit its neighbor list<sup>2</sup> to its nearest base station. The complete sensor network topology can be constructed at one of the base stations. The MCR or the Min-MINMAX problem can be formulated and solved at the base stations. Whenever there is a change in topology we expect that neighboring sensor nodes would inform the base stations.

To determine the link capacities, as in transformation (3) for MCR, we need residual energy of all the sensor nodes at the beginning of each round. As all the nodes have same initial energy and the route taken by each packet is deterministic, we can compute these residual energy values.

In [15], the flow information is transmitted directly to the sensor nodes. As the entire network topology is available at the base stations, routes to be taken by individual *flow information packets* can be determined. Hence, source-based routing can be employed to forward the *flow information packets* to nodes which cannot be reached by the base stations directly. See Figure 3 for a complete overview of our method.

<sup>2</sup>Neighborhood information can be collected by an underlying MAC protocol such as SMACS [8].

## VIII. SIMULATION RESULTS

To compare the performance of Min-MINMAX and MCR routing we simulated a sensor network of 100 nodes randomly distributed in a field of  $100 \times 100$  square-meters. Three base stations were located on the periphery of the sensor network. Each node was provided with an initial energy of 5 Joules. The transmission range of each node was set to 30 meters. The energy spent in transmitting a bit over a 1 meter distance was taken as  $0.1 \text{ nJ/bit-m}^2$  [16] and the energy spent in circuit (transmitting and receiving end) on a bit was set to 50 nJ/bit [16]. The packet length was fixed at 200 bits. Duration of each round was set to 100 time units. We implemented (1) MCF [4], (2) MCR (3) ILP-based [15] (MinMax objective) and (4) Min-MINMAX routing algorithms. We used a network simplex implementation [1] for solving the minimum cost flow and maximum flow problems. We used CPLEX (Version 7.5) for solving the ILP.

The following metrics [15] of evaluation were used.

- 1) Number of rounds until the first node dies.
- 2) Number of rounds until  $\beta$  fraction of nodes either die or have no path to any of the base stations.
- 3) Number of messages received in each round.
- 4) Total number of messages received.
- 5) Energy spent per round.
- 6) Total energy left in the network at the end of the lifetime.

Number of rounds until the first node dies indicates the duration for which the sensor network is fully functional. Number of rounds until  $\beta$  fraction of nodes die, has significance in case of sensor networks where losing a certain fraction of nodes does not effect the application. We choose  $\beta = 0.5$  for comparison of simulation results. Total number of messages received is an indicator of the total amount of information collected during the lifetime of the sensor network. Energy spent per round indicates the energy efficiency of any proposed method. At the end of the lifetime of sensor network, we need to deploy new nodes to continue monitoring of the surroundings. Some of the existing nodes, with enough energy, can continue the sensing task after new nodes are deployed. The last metric indicates the amount of sensing and forwarding task these nodes can handle when the new nodes are deployed.

Figure 4(a), shows the performance of MCF, MCR, ILP-based and Min-MINMAX methods where the metric of comparison is number of rounds before the first node dies. It can be noticed that Min-MINMAX and ILP-based methods clearly outperform the other two methods. Both, MCF and MCR select the least cost path for routing. As a result, the nodes along the least cost path drain their energy quickly and die. On the other hand, in Min-MINMAX and ILP-based methods there is an equitable distribution of energy spent by all the nodes in the network. We repeated the experiment with 150, 200 and 300 sensor nodes. The results can be seen in Figures 4(b), 4(c) and 4(d), respectively. As more nodes are added, the sum total of energy in the network increases. At the same time the number of messages to be routed in a round would also increase. This can explain why lifetime of the

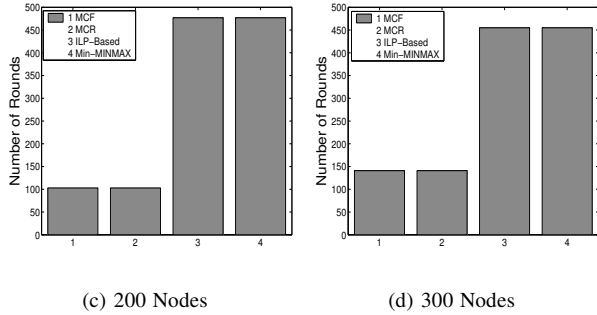
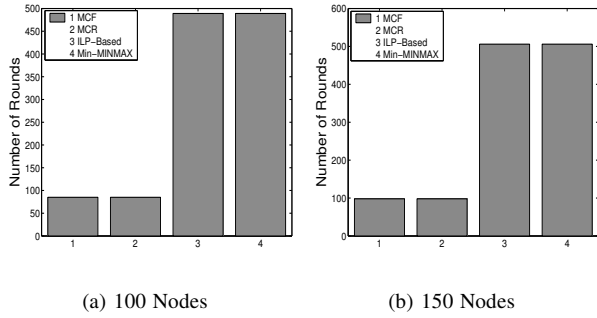


Fig. 4. Number of Rounds Before the First Node Dies

network does not vary significantly in spite of increasing the number of nodes. We can conclude that Min-MINMAX and ILP-based method, irrespective of the network size, perform better when all the sensor nodes are required to be functional throughout the lifetime.

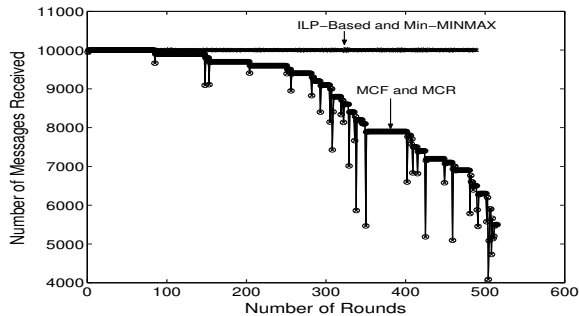


Fig. 5. Number of Messages Delivered in Each Round

Figure 5 compares the number of messages delivered to all base stations in each round until  $\beta$  ( $= 0.5$ ) fraction of nodes die. During the first several rounds all the four methods deliver equal number of messages. But once nodes start failing, we can observe that both MCF and MCR deliver fewer number of messages per round. It is interesting to note that both MCF and MCR perform very similarly. So is the case with ILP-based and Min-MINMAX methods. Another interesting point to note here is that in ILP-based and Min-MINMAX methods the death of first node coincides with the death of  $\beta$  fraction of nodes. From Figure 7(a), we can see that Min-MINMAX and ILP-based methods deliver considerably more number of

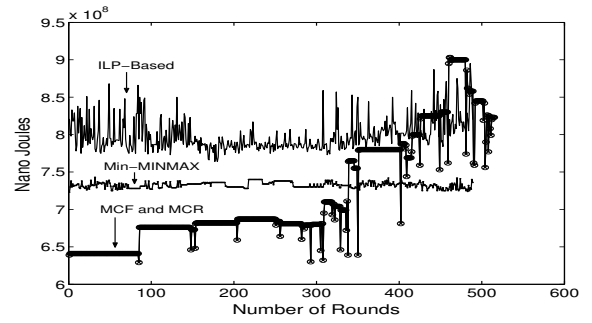


Fig. 6. Energy Spent in Each Round

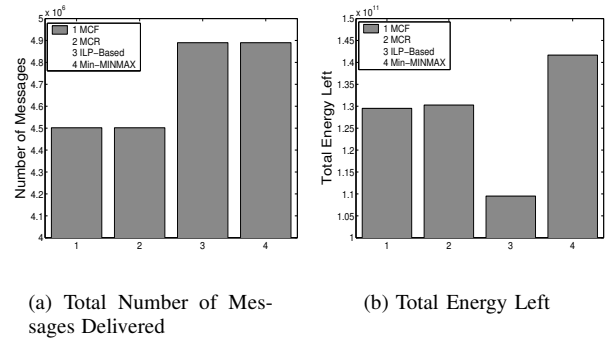


Fig. 7.

messages than MCF and MCR.

While the Min-MINMAX and the ILP-based methods perform similarly in terms of number of messages delivered, Min-MINMAX consumes less energy per round as can be inferred from Figures 6 and 7(b). As expected, during the initial part of the lifetime both MCF and MCR spend less amount of energy than Min-MINMAX. But as nodes die and some least cost paths disappear, MCF and MCR spend more energy than the Min-MINMAX method. It can be noticed that the Min-MINMAX method spends almost same amount of energy throughout the lifetime of the sensor network. Figure 7(b) shows the total energy left in all the sensor nodes at the end of the lifetime. MCF and MCR perform better than the ILP-based method on the total energy left metric. But, we need to notice that the ILP-based method delivered more number of messages than MCF and MCR.

From the above analysis of simulation results we can conclude that Min-MINMAX is a more effective method for increasing the lifetime of the sensor network. From the similarities noticed between Min-MINMAX and ILP-based methods we can conclude that Min-MINMAX performs at par with ILP-based method and consumes less energy per round. Furthermore, unlike the ILP-based method, Min-MINMAX has a well defined bounded running time.

#### A. Impact of Round Duration and Determining the Lifetime

We proposed to split the lifetime of a sensor network into rounds, so that Min-MINMAX can tolerate changes in topology and node failures. To analyze the impact of the round

duration (the value of  $T$ ) on the lifetime of the sensor network, we ran simulations (using the Min-MINMAX routing) by systematically varying the round duration (see Figure 8). An interesting observation is that the lifetime of the network is nearly independent of the round duration. We offer the following explanation: As observed earlier (Figures 4 and 5), the death of the first node in the Min-MINMAX method coincides with (or is followed quickly by) the death of the entire network. Thus, the death of the first node is a good approximation of the death of the entire network while using Min-MINMAX. The duration of round (value of  $T$ ) has little impact on time before the first node dies.

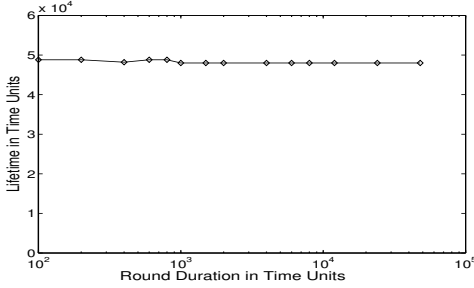


Fig. 8. Impact of Round Duration on Lifetime

From the above observation, we can conclude that the only driving criterion in deciding a round duration is the rate with which topology of the network can change. Furthermore, this observation can be exploited to obtain, a priori (i.e. without performing routing), a lower bound on the lifetime of the network. The maximum value of  $T$  for which the Min-MINMAX problem is feasible is such a bound. We can start with  $T = \text{MAX}_{i \in V_s} \left\{ \frac{RE_i}{C_t} \right\}$  and use a simple binary search procedure (see Figure 9) to determine the maximum value of  $T$  for which the Min-MINMAX problem is feasible. Note that the Min-MINMAX problem is said to be feasible if the net flow reaching the base stations is equal to  $|V| \times T$ . Here,  $\text{MAX}_{i \in V_s} \left\{ \frac{RE_i}{C_t} \right\}$  is the maximum number of time units any node would survive if the node is not required to forward messages originating at other nodes.

## IX. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented two routing algorithms, MCR and Min-MINMAX, for wireless sensor networks with

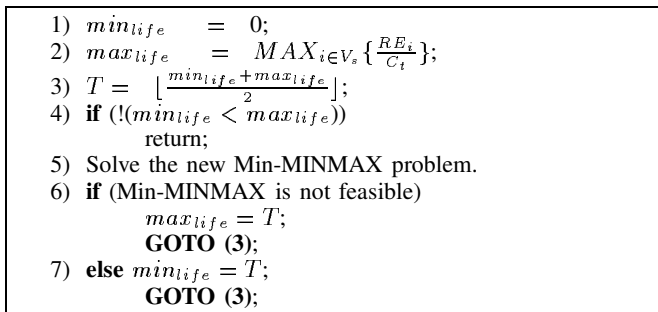


Fig. 9. Binary Search to Determine the Lifetime

static base stations. These algorithms use two polynomially solvable network flow optimization problems, minimum cost flow and maximum flow, to determine the routing information. Through simulation results we have demonstrated that Min-MINMAX routing performs better than MCR and MCF [4]. Furthermore, we have shown that Min-MINMAX performs on par with ILP-based routing on all the metrics and better on both the energy related metrics. We have also shown that the lifetime of the sensor network employing Min-MINMAX routing is independent of the round duration. Using this observation, we have proposed a procedure to determine the lower bound on lifetime of the sensor network.

In this work, we considered proactive sensor networks [2] with no data aggregation. An interesting research direction is towards extending the Min-MINMAX routing to reactive networks [2] with data aggregation. A feasible approach would be to solve the Min-MINMAX problem assuming a proactive network with no data aggregation and then exploit the resulting flow information for routing purposes in the reactive network.

## ACKNOWLEDGEMENTS

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