Max-Min Length-Energy-Constrained Routing in Wireless Sensor Networks*

Rajgopal Kannan Lydia Ray Ram Kalidindi S. S. Iyengar

Department of Computer Science
Louisiana State University
Baton Rouge LA 70803
{rkannan,lydiaray,rkalid1,iyengar}@bit.csc.lsu.edu

Abstract. We consider the problem of inter-cluster routing between cluster heads via intermediate sensor nodes in a hierarchical sensor network. Sensor nodes having limited and unreplenishable power resources, both path length and path energy cost are important metrics affecting sensor lifetime. In this paper, we model the formation of length and energy constrained paths using a game theoretic paradigm. The Nash equilibrium of our routing game corresponds to the optimal length-energy-constrained (LEC) path. We show that this path can be computed in polynomial time in sensor networks operating under a geographic routing regime. We then define a simpler team version of this routing game and propose a distributed nearly-stateless energy efficient inter-cluster routing protocol that finds optimal routes. This protocol balances energy consumption across the network by periodically determining a new optimal path consistent with associated energy distributions. Simulation results testify to the effectiveness of the protocol in producing a longer network lifetime.

1 Introduction

A wireless sensor network is an autonomous system of numerous tiny sensor nodes equipped with integrated sensing and data processing capabilities. Sensor networks are distinguished from other wireless networks by the fundamental constraints under which they operate: a) sensor nodes are untethered and b) sensor nodes are unattended. These constraints imply that network lifetime, i.e., the time during which the network can accomplish its tasks, is finite. Therefore sensors must utilize their limited and unreplenishable energy as efficiently as possible.

Sensor network architectures can be broadly classified into two main categories: flat and hierarchical-cluster based [9]. In a hierarchical sensornet, efficient energy management is potentially easier since routing is partitioned into intra-cluster and inter-cluster, with traffic between clusters being routed through corresponding cluster heads.

A significant amount of research has been done on hierarchical sensornets, for example, [9]. Most of these architectures are based on the assumption that cluster heads or gateway nodes can communicate directly with each other and the transmission power is adjustable at each node. In this paper, we consider a more realistic two-level architecture where cluster heads (called *leader nodes*) must use the underlying network infrastructure for communication.

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The primary issue addressed in this paper is energy-constrained inter-cluster routing within the framework of the proposed architecture, i.e., leader to leader and leader to sink routing. Since sensor nodes on a route consume energy continuously by sending and receiving data packets, the longevity of a sensor node is inversely proportional to the number of routes it participates in. Network partition is therefore expedited by uneven energy distribution across sensors, resulting from improperly chosen routes. Ideally, data should be routed over a path in which participating nodes have higher energy levels relative to other non-participating nodes. Network operability will be prolonged if a critically energy deficient node can survive longer by abstaining from a route rather than taking part in a route for a small gain in overall latency. Therefore, both *path length* and *path energy cost* are critical metrics affecting sensor lifetime.

While there are several existing protocols in the literature that focus exclusively on either of these issues, there has only been some recent work that considers both aspects. For example, Shah and Rabaey [10] describe a probabilistic routing protocol where non least-energy cost paths are chosen periodically. In [8], a node attempts to balance energy across all its neighbors while finding shortest paths to the sink. However, there is no unified analytical model that explicitly considers routing under both the constraints of energy efficiency and path length. We observe that the choices of sensor nodes under these constraints are a natural fit for a game theoretic framework. In this paper, we propose a game theoretic paradigm for solving the problem of finding energy-optimal routing paths with bounded path length. We define a routing game in which sensors obtain benefits by linking to healthy nodes while paying a portion of path length Thus sensor nodes modelled as intelligent agents cooperate to find optimal routes. Our proposed model has the following benefits:

- Each player will tend to link to the healthiest possible node. Thus network partition will be delayed.
- Since each node shares the path length cost, path lengths will tend to be as small as possible. Thus delay is restricted in this model. Also smaller path lengths will prevent too many nodes from taking part in a route, thereby reducing overall energy consumption.

The Nash equilibrium of this routing game defines the optimal length-energy-constrained (LEC) path. We show that while computing this path is NP-hard in arbitrary sensor networks, it can be found in polynomial time (in a distributed manner) in sensor networks operating under a geographic routing regime.

We next propose a fully distributed and nearly stateless inter-cluster routing protocol which implements a simplified team version of the above routing game using a metric called *energy weakness*. The protocol determines the route with least weakness by combining limited global information on node energies obtained through *reverse directional flooding* (RDF) along with local geographic forwarding. While RDF involves some extra overhead and consumes node energy, global information obtained through this process ensures a significant tradeoff in terms of node energy balancing and network lifetime. Note that this protocol can be easily modified to implement a distributed version of the original game as well. The key features that distinguish our protocol from other related routing protocols are summarized below.

- Unlike network lifetime maximization protocols such as [4] which require global information on current data/packet flow rates from each sensor to sink(s), our protocol utilizes very limited network state information and is thus easily implementable.

- Since energy is a critical resource in sensor networks, depleted regions, i.e regions with low residual node energies must be detected and bypassed by routing paths as quickly as possible. This is analogous to congestion in wired networks. We propose a new technique for indicating the onset of energy depletion in regions by using *energy depletion indicators*. This is used in conjunction with the energy weakness metric in our protocol to ensure energy-balanced routing.
- Geographic sensornet routing algorithms such as GPSR [6] and GEAR [8] employ elegant neighbor selection procedures using only local network information. These mechanisms enhance energy savings at individual sensor nodes and are easy to implement. However due to their predominantly local nature, there are situations in which these protocols will be slow to adapt to changing energy distributions in the network. For example, consider a region in a sensornet that is intersected by multiple routes and thus has higher energy depletion rates. While GEAR is likely to take a considerable amount of time to avoid this region through localized rerouting, our protocol, with its energy depletion indicator algorithm, will quickly detect such regions and establish new bypass routes.
- A potential drawback of protocols such as [8], [6], [11] which use local geographic forwarding is that significant backtracking is required when a hole is encountered. This situation is completely eliminated by our protocol since packets are forwarded according to the periodically updated routing table residing at each node.
- In protocols such as [8] [6] [3] [2], a single routing path (typically, the least energy path) is utilized continuously until a node's energy is completely exhausted. While the motivation behind this approach is to save energy consumption at individual sensor nodes, this might lead to unintended consequences such as the expedited partition of the network. Our protocol overcomes this drawback by selecting new length-energy-constrained routing paths periodically. ([10] also does this but in a probabilistic manner for non least-energy cost paths).
- Many of the previously proposed routing protocols are source-initiated i.e. the source predetermines the routes [3] [2]. The ad hoc infrastructure of a sensornet makes the implementation of a centralized system extremely expensive. Our protocol reduces communication cost to a great extent by accomplishing localization of routing decisions.

We have evaluated our routing protocol using the ns-2 simulator. Simulation results indicate that compared to [6] and [8], the protocol is enormously effective in reducing energy deviation thereby leading to equitable residual energy distribution across the sensor network. Thus the protocol should have a significant impact on sensor network survivability.

The rest of the paper is organized as follows. Section 2 describes the proposed architecture while section 3 contains the analytical model along with the proposed leader to leader routing protocol. In section 4, we describe methods for selecting routing protocol parameters. Section 5 evaluates protocol performance and conclusions are derived in section 6.

2 Network Architecture

The sensornet architecture proposed in this paper has a two-level hierarchy as shown in Figure 1. The lower level consists of a standard wireless sensor network. At the upper level, an overlay network is created among a collection of special sensor nodes (called *leader nodes*) at specific locations. Note that these leader nodes are selected from the underlying sensor

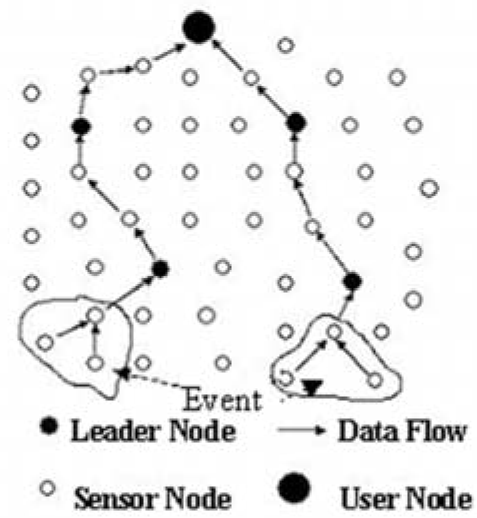


Fig. 1. Proposed Network Architecture

network and occupy positions similar to cluster heads. In general, leader nodes are expected to be less energy-constrained than ordinary sensor nodes[1] and are responsible for aggregated leader to leader and leader to sink communication. Unlike existing clustered architectures, the proposed network is significantly different in that we do not assume direct connectivity among leader nodes. Instead, leader to leader communication utilizes underlying network infrastructure. Note that the routing responsibility of leader nodes does not preclude in any ways their functioning as sensors. Our hierarchical architecture is flexible enough for any sensor to function as a leader node. Mechanisms by which the ordinary sensors become leader nodes are not discussed in this paper. The main features of the proposed architecture are as follows:

- Sensors are assumed to be fixed (i.e. immobile).
- Each leader node is responsible for aggregating sensor data (in response to queries) from sensor nodes within a predefined neighborhood. This is similar to the clustering approach proposed in [9] but with significant differences in the way the cluster heads communicate with each other.
- Leader nodes route/communicate aggregate sensor data to other leader nodes and sinks via ordinary sensors as intermediaries. Communication of aggregate sensor data between leader nodes should result in the reduction of overall network traffic.

[1] This is not strictly necessary for our architecture to work. However, since leader nodes have extra responsibilities, this is a reasonable expectation.

Since leader to leader communication has an impact on energy consumption of ordinary (intermediate) sensors too, the development of efficient protocols is of paramount importance in this architecture. In the next section, we propose an analytical model of length-constrained energy efficient leader to leader routing along with practical implementation.

3 Analytical Model of Leader to Leader Routing

A sensor network is useful as long as sensors continue to process and route data. Since sensor nodes on a route consume energy continuously by sending and receiving data packets, the longevity of a sensor node is directly proportional to the number of routing paths it participates in. Improperly chosen routing paths will lead to uneven energy consumption across sensors in the network. A highly non-uniform distribution of residual energies in sensors over the network might also expedite network partition. Therefore we must design leader to leader routing protocols that dissipate energy equitably over sensors in order to enhance network survivability.

One possible approach is to prevent low energy nodes from taking part in a route as long as they are energy-deficient relative to their neighbors. However, a route that focuses only on energy efficiency may be undesirably long since the lowest energy-cost path need not be the shortest. Conversely, if path length is measured in terms of number of hops, longer paths will result in energy depletion at more sensors while also increasing delay. When path length is measured in terms of Euclidian distance, longer paths lead to higher energy consumption at individual sensors since transmitting power is proportional to neighbor distance. While there are several existing protocols in the literature that focus exclusively on either of these issues, there is no unified analytical model that explicitly considers routing under both the constraints of energy efficiency and path length.

In this paper, we model sensors as intelligent agents and propose a game theoretic paradigm for solving the problem of finding energy-optimal routing paths with bounded path length. The equilibrium point(s) of the routing game define the optimal routing path. We then define a team version of this routing game and propose a distributed nearly-stateless leader to leader energy efficient routing protocol that finds the optimal route. We now formally define our analytical model and formulate the routing game.

Let $S = \{s_1, s_2, \ldots, s_n\}$ be the set of sensors in the sensor network participating in the routing game. Let L_1 and L_2 be a pair of leader nodes using sensors in S as intermediaries[2]. Data packets are to be routed from L_1 to L_2 through an optimally chosen set $S' \subset S$ of intermediate nodes by forming communication links. Note that we do not consider multicast communication between sets of leader nodes in this paper.

Strategies: Each node's strategy is a binary vector $l_i = (l_{i1}, l_{i2}, ..., l_{ii-1}, l_{ii+1}, ..., l_{in})$, where $l_{ij} = 1$ ($l_{ij} = 0$) represents sensor s_i's choice of sending/not sending a data packet to sensor s_j. Since a sensor typically relays a received data packet to only one neighbor, we assume that a node forms only one link for a given source and destination pair of leader nodes. In general, a sensor node can be modeled as having a mixed strategy [1], i.e., the l_{ij}'s are chosen from some probability distribution. However, in this paper we restrict the strategy space of sensors to only pure strategies. Furthermore, in order to eliminate some trivial

[2] In general, sensors in S will be simultaneously participating in routing paths between several such pairs.

equilibria, each sensor's strategy is non-empty and strategies resulting in a node linking to its ancestors (i.e. routing loops) are disallowed. Consequently, the strategy space of each sensor s_i is such that Prob. $[l_{ij} = 1] = 1$ for exactly one sensor s_j and Prob. $[l_{ij} = 1] = 0$ for all other sensors, such that no routing loops are formed.

Payoffs: Let $l = l_1 \times l_2 \times \ldots \times l_n$ be a strategy in the routing game resulting in a route $\mathcal{P}$ from source to destination leader node. Each sensor on $\mathcal{P}$ derives a payoff from participating in this route. The payoff of a sensor s_i which links to node s_j in $\mathcal{P}$ is then defined as:

$$\pi_i(l) = E_j - \xi L(\mathcal{P}) \tag{1}$$

where E_j is the residual energy level of node s_j and $L(\mathcal{P})$ the length of routing path $\mathcal{P}$. E_j represents a benefit to s_i, thus inducing it to forward data packets to higher energy neighbors. The parameter ξ represents the proportion of path length costs that are borne by sensor s_i. Choosing ξ as a positive constant or proportional to path length will inhibit the formation of longer routing paths. Conversely, setting ξ zero or inversely proportional to path lengths will favor the formation of paths through high-energy nodes. We choose xi as a non-zero positive constant for this routing game. Thus each sensor will forward packets to its maximal energy neighbor in such a way that the length of the path formed is bounded. This model encapsulates the process of decentralized route formation by making sensor nodes cooperate to achieve a joint goal (shorter routing paths) while optimizing their individual benefits.

A Nash equilibrium of this game corresponds to the path in which all participating sensors have chosen their best-response strategy, i.e., the one that yields the highest possible payoff given the strategies of other nodes. This equiilibrium path is the optimal Length Energy-Constrained (LEC) route in the sensor network for the given leader pair. Note that the process of determining the LEC route requires each node to determine the optimal paths formed by each of its possible successors on receiving its data. The node then selects as next neighbor that node, the optimal path through which incurs the highest payoff.

Theorem 1 Let $\hat{\mathcal{P}}$ be the optimal LEC route for a pair of source and destination leader nodes in an arbitrary sensor network. Computing $\hat{\mathcal{P}}$ is NP-Hard.

This proposition can be proved by reduction from Hamiltonian Path. For lack of space we do not include the proof in this paper.

Theorem 2 Let S be any sensor network in which sensor are restricted to following a **geographic routing** *regime. In other words, the strategy space of each sensor includes only those neighbors geographically nearer to the destination than itself. Then $\hat{\mathcal{P}}$ can be computed in polynomial time in a distributed manner.*

Again, due to space limitations, we only provide an outline of the proof. $\hat{\mathcal{P}}$ can be obtained in $O(N + E)$ steps for an arbitrary N-node geographically routed sensor network with E edges and $O(N)$ steps in a $\sqrt{N} \times \sqrt{N}$ mesh. The result hinges on the observation that in a geographically routed network, the intersection of all feasible paths from the source to a node s_i and from s_i to the destination node is empty (except for s_i). Thus one can compute the union of optimal paths from source leader to sensor and sensor to destination leader.

Next, we identify sufficient conditions under which the optimal LEC path coincides with other commonly used routing paths. For brevity, we state these results without proof.

Proposition 1: Let E^i_{max} and E^i_{min} denote the maximum and minimum neighbor node energies at sensor s_i. Then the shortest path from L_1 to L_2 will be optimal if

$$E^i_{max} - E^i_{min} < \xi(\delta S) \tag{2}$$

holds at each sensor node s_i on the shortest path, where (δS) is the difference between the shortest and second shortest paths from s_i to L_2.

Let the maximal-energy neighbor path denote the one obtained by following the maximal energy nodes from L_1 to L_2 such that a path is formed. Then we have,

Proposition 2: The maximum energy neighbor path will be optimal if

$$(\delta E) > \xi(l_h - l_s) \tag{3}$$

holds at every node s_i on the path, where (δE) is the difference in energies between the maximal and second maximal neighbors of s_i and, l_h and l_s are the lengths of the maximal energy and shortest paths from s_i, respectively.

4 Distributed Protocol Implementation

We describe a distributed implementation of the optimal LEC routing protocol in terms of a simplified 'team' version of the routing game. This team-game routing protocol can be easily modified to obtain optimal LEC paths as well and is simpler to describe. In the team LEC path heuristic, each node on a path shares the payoff of the worst-off node on it. Formally, let $\mathcal{L}$ be the set of all distinct paths from a particular source and destination leader pair. Let $E_{min}(\mathcal{P})$ be the smallest residual energy value on path $\mathcal{P}$. Then the equilibrium path of the team LEC game is defined as:

$$\hat{P} = \text{argmax}_{\mathcal{P}\in\mathcal{L}}(E_{min}(\mathcal{P}) - \xi|\mathcal{P}|) \tag{4}$$

For simplicity in the protocol description below, we set ξ to zero. However the protocol can be easily modified for non-zero ξ as well as for computing optimal LEC paths in the original LEC game. We interpret the optimal path under this condition as follows: Given any path $\mathcal{P}$, the durability of the path is inversely proportional to $E_{min}(\mathcal{P})$. A path with lower average energy but higher minimum energy should last longer than a route with the opposite attributes since the least energy node is the first to terminate and make that route obsolete. Thus the inverse of the minimum node energy on a given path reflects the energy weakness of the path. The proposed protocol will select an optimal path of bounded length with the least energy weakness. Since node energy levels are changing continuously in a sensor network due to sensing, processing and routing operations, the optimal path needs to be recomputed periodically. Thus the proposed protocol operates in two different phases: data transmission and path determination as described below:

4.1 Data Transmission Phase

During this phase, data packets are transmitted from one leader node to the other through the optimal path (with least energy weakness). Each data packet also potentially collects information about the energy consumption en route, by keeping track of residual energy levels of nodes on the path. When energy levels of a given critical number of nodes fall below a certain threshold, the data transmission phase ends and the new optimal path determination phase begins.

The fundamental steps of the data transmission phase are as follows:

- Each data packet is marked by the source leader node with the geographical position of the destination node and with a threshold value th. Each data packet contains a special n-bit Energy Depletion Indicator (EDI) field, where $n <<$ packet size.
- Each sensor node receiving a data packet determines whether its energy level has fallen below the threshold th. If so, and the EDI field in the data packet is not exhausted, the node sets a single bit in the EDI field. Then it forwards the packet to the best next-hop neighbor according to its routing table. We assume that before the network starts any activity, all ordinary 'non-leader' sensor nodes have the same energy level. Therefore, during the first data transmission phase, the best next-hop neighbor of a node is the one which is geographically nearest to the destination leader node. In all other phases, the routing table is updated according to the optimal LEC path calculation.
- If the receiver leader node gets a data packet with all n bits in the EDI field set to 1, it triggers a new optimal path selection procedure. Alternatively, if the destination receives n data packets with at least one bit in the EDI field set to 1 a path determination phase is triggered.

Calculation of the Threshold Value The threshold value th plays a very important role in the data transmission phase since it is used to provide an approximate indication that the current optimal path has become obsolete. Intuitively, th must be a function of the current residual node energy levels in the network. In this paper, we use the following function:

$$th = \beta E_{min} \tag{5}$$

where $0 < \beta < 1$ and E_{min} is the minimum energy level in the current optimal path. Since E_{min} changes with time, the threshold is recalculated in each path determination phase, consistent with the current energy distribution across the network.

4.2 Path Determination Phase:

This phase begins when the destination leader node receives critical EDI information and ends when the sending leader node has updated its routing table and recalculated the threshold value. The principle steps are as follows:

- The destination leader node L_2 triggers this phase by flooding the network with control packets along the geographic direction of the source leader node L_1 (Figure 2). Note that this *reverse directional flooding* occurs in the direction opposite to that of data transfer.
- Each node forwards *exactly one* control packet to all its neighbors in the geographic direction of L_1. Each control packet contains a field EM_p that indicates the maximum of the minimum energy levels of all partial paths converging at the given node, i.e., the inverse of the energy weakness of the 'strongest' partial path.

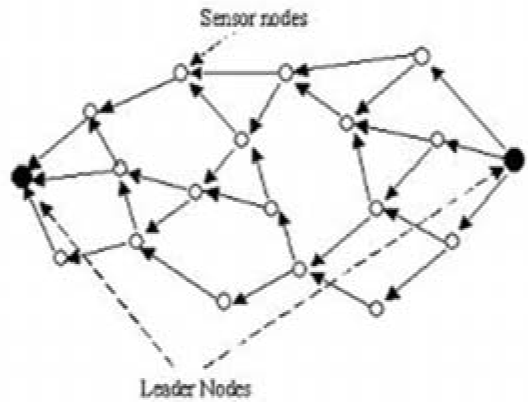


Fig. 2. Reverse Directional Flooding

- On receiving the first control packet, each node sets a timer for a prefixed interval T. This time-period should be large enough for the node to receive future control packets from most of its neighbors (corresponding to different partial paths from the leader node terminating at this node), but not so large as to cause high delays. With each arriving control packet, the node updates and stores the highest EM_p value seen so far. *However, if its own energy level E_i is lower than all these values it stores E_i.* With each control packet, it also updates its routing table for destination L_2 to point to the node from which it has received the highest energy control packet. Note that this part of the protocol can be easily modified to incorporate path lengths in addition to the minimum energy computations above.
- When the timer expires, this node forwards a new control packet with EM_p field set to the stored energy value to all its neighbors in the geographic direction of L_1. Control packets arriving after the timer expires are discarded.
- Eventually, L_1 begins receiving control packets and sets its timer. Its value of T can be determined in many ways depending on the specific requirements of applications. In this paper, we calculate T to ensure that most of the paths from L_1 to L_2 are included in the optimality calculations. If (D_{max}) is the maximum transmission delay between two nodes, the value of T is determined as $(MINHOP * D_{max})$, where $MINHOP$ is an estimate of the shortest path from L_1 to L_2. This value can be estimated apriori using GPSR routing [6] before the first data transmission phase. Note that the given value of T allows control packets from paths up to twice the length of the shortest path to be forwarded to $L - 1$. Also note that D_{max} is a function of the specific MAC-layer protocol being implemented in the sensor network. Finally, when the timer expires at L_1, it selects the final E_{min} value as the highest EM_p value it has received, calculates the new value of th and sets its routing table accordingly. The next data transmission phase can now begin.

5 Selection of Parameters

There are three main issues related to practical implementation efficiency of our protocol.

- To avoid unnecessary energy expenditures, control packets must be prevented from hanging around the network after the path determination phase. The parameter MINHOP serves this purpose.
- There is a tradeoff between energy consumption involved in flooding vs the gain in network lifetime due to equitable energy distribution among sensors. Therefore, frequency of invocation of the path determination phase is an important parameter. We experimentally model this using β and EDI as described later.
- Calculating the energy overhead of flooding in the path determination phase is also an important issue. We provide analytical upper bounds and discuss optimizations for further reducing this control overhead.

5.1 Selection of β

Data transmission in the proposed protocol ends when residual energy levels of at least n nodes on the current path fall below threshold th. With high β, the smaller the threshold value, and the larger the useful data transmission phase. If the traffic is fairly bursty, th should be large so that data packets in the burst can be transmitted. β is an empirical value and can be modified based on previous observations. A useful rule of thumb to set the value of β for the current period is as follows:

$$\beta_{current} = \alpha\beta_{prev1} + (1 - \alpha)\beta_{prev2} \tag{6}$$

where $0 \leq \alpha \leq 1$, β_{prev1} and β_{prev2} are the previous and previous to previous values of β correspondingly. α should be chosen according to the specific requirement i.e. whether the current value of β should be increased or decreased and to what extent.

5.2 Selection of Energy Depletion Indicator

Energy depletion indicator is an integer which indicates the maximum number of critical nodes allowed during a data transmission period. The main contribution of energy depletion indicator is to regulate the duration of data transmission phase. The higher the value of this parameter, the longer the period of data transmission. Like β, this parameter is also empirical and can be modified based on pervious observations. A rule of thumb similar to that of β can be used to modify the value of this parameter. Thus,

$$EDI_{current} = \gamma EDI_{prev1} + (1 - \gamma)EDI_{prev2} \tag{7}$$

where $0 \leq \gamma \leq 1$, EDI_{prev1} and EDI_{prev2} are the previous and previous to previous values of EDI correspondingly. γ should be chosen according to the specific requirement i.e. whether the duration of the data transmission phase should be increased or decreased and to what extent.

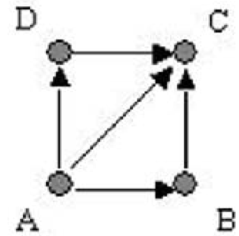


Fig. 3. Possible Control Packet Optimization

6 Overhead Due to Path Determination

The proposed protocol uses directional flooding technique to determine a new optimal path. The advantage of using directional flooding over general flooding is that the packets being forwarded only to a single direction produces less overhead. The following propositions 9stated without proof, for brevity) give an estimate of overhead due to directional flooding in terms of number of control packets.

Proposition 3:*In a general N node geographically routed wireless sensor network where a node can have at most k neighbors, the number of control packets transmitted during the path determination phase is bounded by kn.*

Proposition 4:*In a wireless sensor network as an $\sqrt{N} \times \sqrt{N}$ mesh, the number of control packets transmitted during the path determination phase is bounded by $3\sqrt{N}$.*

Note that in a mesh topology, the actual number of control packets transmitted during the path determination phase can be reduced further. Consider the following situation shown in Figure 3. In this portion of the mesh, node A sends control packets to nodes B, C and D. If B receives the packet from A before its timer expires and if the energy value on this packet is the winning value at B as well, then B does not need to send this packet to node C (which has already received a copy of the same packet from A). In this manner, the total number of control packets can be further reduced.

7 Performance Evaluation

The main objective of our protocol is to gradually balance unfair energy consumption across the network. To evaluate performance of this protocol, we use the following metrics which reflect dispersion or concentration of energy consumption across a network.

- **Variance of energy level**: The variance of the energy levels of all the nodes is the primary measure of dispersion. A high variance indicates higher energy consumption at some of the nodes compared to others.
- **Range of energy level**: This metric measures the difference between the energy levels of the maximum energy node and the minimum energy node over the whole network. A large value for this range is a result of unfair distribution of routing load among the nodes.

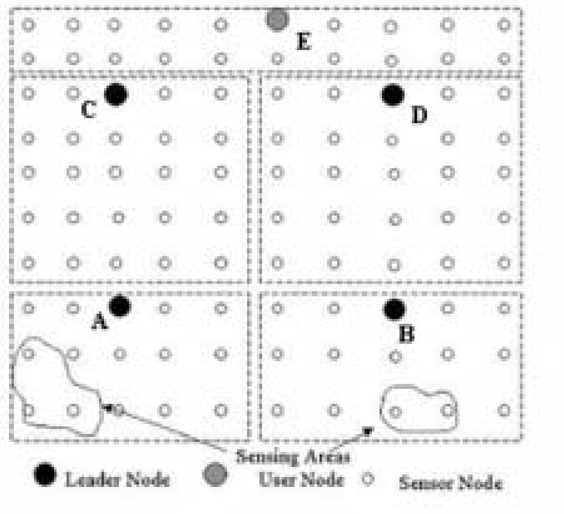


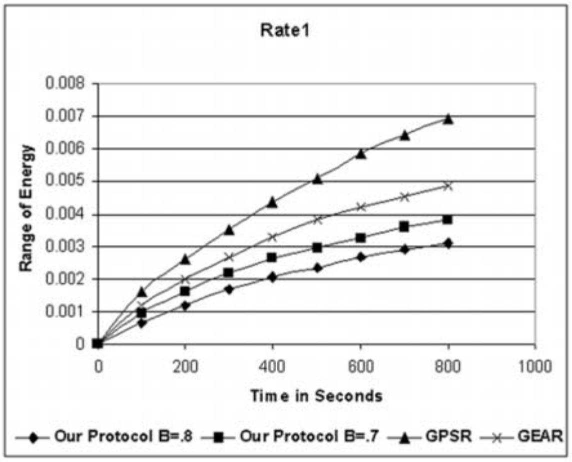
Fig. 4. Simulation Topology

7.1 Experimental Setup

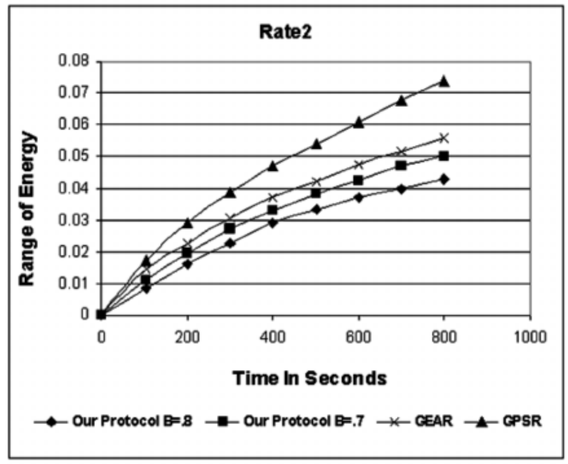
In our simulation we have 100 nodes in a 1000×1000 meter area, with one node at each of the positions of the 10×10 square grid. Figure 4 represents the mesh topology that we have used for evaluating our protocol. The whole network is divided into five clusters. There are two sensing areas in the regions under clusters A and B. Sensor data packets are generated from these sensing areas at a uniform rate. The leader nodes in each of the clusters A and B collect these packets and send them to the leader nodes of clusters C and D respectively via intermediate sensor nodes. Leader nodes C and D forwards these packets to the sink node in cluster E. Each leader node selects the leader node which is geographically nearest to the sink for transmitting its received/sensed data. Leader to leader communication is accomplished through ordinary sensors. Reverse directional flooding is initiated when a leader node receives a sensor data packet indicating that at least *three* sensor nodes are close to the threshold th. A sender leader node sets th to the new βE_{min} obtained from the reverse flooding phase. We run the simulation for 900 seconds and compare three protocols for energy efficiency: geographic shortest path routing (GPSR [6]), GEAR [8] and the proposed team LEC protocol. These experiments are carried out on our simulation test-bed which is an extension of Sensorsim [7].

7.2 Results and Analysis

We assume that before the network starts any activity, all ordinary sensor nodes have the same energy level. Therefore, in the very beginning, energy distribution is uniform across the network. When a network becomes active, the energy distribution across it gradually becomes non-uniform since nodes participating in a route inevitably consume more energy than other nodes. A protocol which uses a fixed route until one node in the route is completely drained out of its energy, ends up in producing an energy distribution with high



(a) *Rate*1



(b) *Rate*2

Fig. 5. Range of residual energy levels across the network with team LEC routing , GEAR and GPSR

dispersion of energy levels. On the other hand, our proposed protocol tries to adapt to the dynamically changing energy distribution and gradually uniforms the initial uneven energy distribution. Therefore, it is expected that the difference between the dispersion measures produced by our protocol and those produced by any protocol with fixed routing will increase with an increasing rate with time. In this paper, we compare the performance of our protocol with that of a protocol which uses a fixed shortest path for leader to leader communication.

Results of our simulation comparing performance of our protocol with that of GEAR and GPSR reflect the outcome as expected. We use *range* (the difference between the maximum and minimum value of a distribution) and *variance* as measures of dispersion of energy distribution to evaluate our protocol. In Figure 5(a) and 5(b), we present the difference in the ranges of node energy distributions across the network over time under the three protocols with two different values of β and two different traffic rates. In both the figures, the difference of the ranges rises very sharply indicating that our protocol yields lower range of energy distribution compared to that produced by the fixed route protocol as time proceeds. Moreover, with an increased traffic rate, our protocol produces a much better result compared to that of shortest path routing. This indicates that with heavy traffic, the energy distribution across the network become more uneven in a fixed route protocol since the load is heavier on a particular route. In this case, frequent change of routing path is very much useful to bring uniformity to overall energy consumption. Note that routes being changed more frequently with a higher value of β, performance of the proposed protocol is better when $\beta = 0.8$ than that when $\beta = 0.7$.

Figure 6 represents the variance of residual energy distribution produced by our protocol with two different β values and that by GPSR and GEAR. The energy range metric does

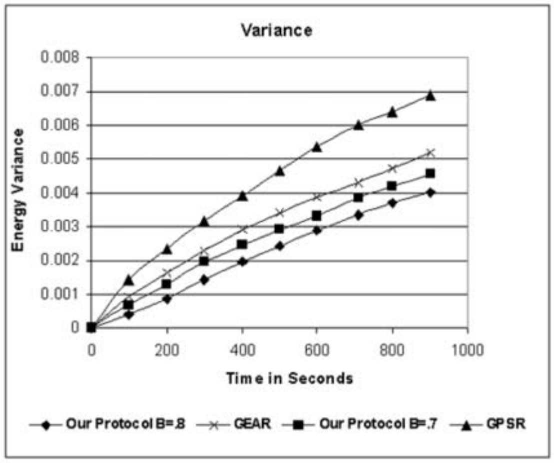


Fig. 6. Variance in residual energy levels across the network under team LEC routing with $\beta = 0.8, 0.7$, GEAR and GPSR

not measure the number of sensor nodes that are being treated unfairly. The high variance of the shortest path routing indicates that a significant number of sensor nodes are being treated unfairly with network traffic being concentrated at fewer nodes. This might expedite partition of the network due to energy depletion at critical nodes. With higher value of β, the proposed protocol produces lower variance due to more frequent route changes.

Figures 7 shows how the difference between the minimum energy level produced by our protocol and that by GPSR and GEAR changes with time for two different β values. In both the cases, the difference rises very sharply as time proceeds. With a higher value of β, the rise is sharper because change of route is accomplished more frequently and therefore, consumption of energy is more uniform under our protocol.

8 Conclusion

In this paper, we describe a game theoretic paradigm for inter-cluster routing in a clustered sensornet architecture in which cluster heads utilize underlying network infrastructure for communication. The max-min energy balancing inter-cluster routing protocol finds the length-energy-constrained path corresponding to the equilibrium of the routing game. This protocol balances energy consumption across the network by selecting new optimal paths periodically. The simulation results indicate effectiveness of this protocol for enhancing network survivability.

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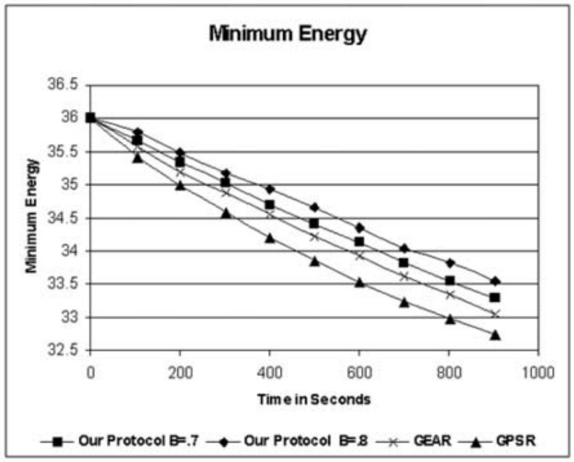

Fig. 7. minimum residual energy levels across the network under team LEC routing with $\beta = 0.8, 0.7$, GEAR and GPSR

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