Threshold-Energy Constrained Routing Protocol for Wireless Sensor Networks*

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Abstract

We propose a novel fully distributed and nearly stateless routing protocol for inter-cluster routing via intermediate sensor nodes in a hierarchical sensor network. The protocol determines energy-efficient short paths to the destination by dynamically computing energy thresholds to prevent energy-deficient nodes from particpating in routes, in essence using limited global information on node energies along with local geographic forwarding. The proposed protocol bounds the minimum energy level of any node from below by at most one packet transmission cost from the threshold value. Analogous to congestion indicators in wired networks, a novel mechanism using energy depletion indicators in conjunction with global energy thresholds is used to periodically reroute and balance energies. Simulation results also show that using limited global information leads to significant improvement in node-energy distribution and network lifetime.

Keywords: Energy-Constrained Routing, Sensor Networks, Energy Threshold, Geographic Routing

1 Introduction

Wireless sensor networks are autonomous systems of tiny sensor nodes equipped with integrated sensing and data processing abilities. Sensors (continously) collect data from the surrounding environment to be aggregated and routed to the base station (sink) in response to queries [1]. Unlike typical ad-hoc networks, sensor nodes are heavily energy-constrained and network lifetime is finite. Routing algorithms must be therefore be designed to utilize limited and unreplenishable energy resources as efficiently as possible.

Sensor networks architectures can be broadly classified into either *flat* or *hierarchical*–cluster based [2]. In hierarchical sensornets, routing is partitioned into intra-cluster and inter-cluster, with traffic between clusters being routed through corresponding cluster heads. Efficient energy management is potentially easier in hierarchical sensornets due to this division.

A significant amount of research has been done on routing in hierarchical sensornets ([2], [3]). While these protocols are efficient in design, they rely on the assumption that cluster heads can communicate directly with each other. This imposes strict constraints on positions of these nodes and therefore may be unrealistic for wireless sensor networks. Here, we consider a more realistic two-level hierarchical architecture where cluster heads called *leader nodes* must use the underlying network infrastructure for communication, i.e., leader to leader and leader to sink routing.

In this paper, we propose a new routing protocol for energy-constrained inter-cluster routing that combines the usage of limited global information on node-energies with local geographic forwarding, in which packets are forwarded to neighbors in the geographic direction of the destination. This energy-efficient geographic routing protocol is fully distributed and routes data over paths in which participating nodes have

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[*] Manuscript Received August 28, 2003, Accepted September 5, 2003
[†] This work was supported in part by NSF grants ITR-0312632, IIS-0329738 and DARPA/AFRL #F30602-02-1-0198

higher energy levels relative to other non-participating nodes. A global energy threshold metric is periodically recalculated using limited *reverse directional flooding* to prevent critically energy-deficient nodes from taking part in routes until current energy distributions in the network become more balanced. In particular, the proposed threshold-constrained geographic routing protocol finds the energy-constrained shortest path to the destination, i.e the geographically shortest path in which all nodes have residual energy levels above the calculated threshold. Our motivation in obtaining (limited) global energy information through reverse directional flooding (which involves some extra overhead and consumes limited node energy) is to ensure a significant tradeoff in terms of node energy balancing and network lifetime. The key features distinguishing our protocol from related routing protocols in the literature are summarized below.

- Network lifetime maximization protocols such as [6] require global information on current data/packet flow rates from each sensor to sink(s). Linear programming and other techniques are then used to calculate routes for maximizing network lifetime. These protocols require significant global network state information and are consequently difficult to implement. In contrast, the proposed protocol requires very limited network state information to calculate threshold values.

- 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 threshold energy levels in our protocol to ensure energy-balanced routing. Intuitively, the protocol ensures that the minimum energy level of any node is bounded below by at most one packet transmission cost from the threshold value.

- Geographic sensornet routing algorithms such as GPSR [5] and GEAR [4] are well-known protocols which combine energy aware neighbor selection with geographic forwarding. The neighbor selection procedure in GEAR is based on a parametric combination of local information such as node energy consumed to date, and node distance to destination. While this is a very elegant and easily implementable protocol, there are situations in which the protocol will be slow to adapt to changing energy distributions, due to its predominantly localized nature. For example, consider a region in a sensornet which is intersected by multiple routes. Nodes in this region will tend to deplete energy at higher rates. While GEAR will take a considerable amount of time to avoid this region through localized rerouting, our proposed protocol using a limited global threshold mechanism, will be able to detect higher energy depletion rates quickly and find a new route in comparatively lesser time.

- In protocols such as [5] [7] [8], 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 expedited partition of the network. Our protocol overcomes this drawback by selecting new routing paths periodically.

- Many of the previously proposed routing protocols are source-initiated i.e. the source predetermines the routes [7] [8].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 a variant of the ns-2 simulator [10]. Simulation results indicate that the protocol is quite effective in reducing energy deviation as measured by energy range and energy variance across the network as compared to GPSR and GEAR, thereby leading to equitable residual energy distributions. Simulation results also show that our protocol results in higher minimum residual energy levels of the sensor network. These metrics indicate that 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 threshold-constrained and geographic leader to leader/sink routing protocol. In section 3, we describe methods for selecting protocol parameters along with a brief discussion about reverse directional flooding overhead. Section 4 evaluates protocol performance and conclusions are derived in section 5.

2 Proposed Routing Protocol

Enhancing network connectivity/survivability through energy-balanced routing of sensor data through the sensor network is a desirable attribute of any energy-constrained routing protocol. A centralized solution to the problem of determining data paths that lead to equitable energy-dissipation among all sensors would require global network state information and prohibitive communication and computational overhead. In this paper we propose a new distributed protocol for routing packets between leader nodes in a sensor network. The primary objective of the protocol is to balance the routing load among sensors by choosing routes in a distributed energy-aware manner with the concomitant side-effect of ensuring long-term network connectivity. Our energy-balanced routing approach relies on preventing sensor nodes with current energy levels below a certain threshold from taking part in the routing process. Since sensor nodes cannot *refuse* to forward packets once received, the key intuition behind our protocol is to prevent critically energy-deficient nodes from receiving packets for forwarding as long as their energy-deficient state is maintained relative to their neighboring nodes. The threshold energy value is computed periodically based on some local network state information. The routing decision between any pair of leader nodes is independent of the decision for routing between any other pairs. The routing parameters that we use are threshold energy values and the hop-count between the sender and the receiver leader nodes. Details of the protocol are provided below.

2.1 Threshold Routing Protocol

The proposed routing protocol has three main features:

1. Geographic forwarding is used to direct packets between leader nodes. We assume that each sensor node can determine the set of geographically closer neighbors to the given destination coordinates as in [5], [4].
2. Threshold energy levels are used to determine the eligibility of a sensor node for participating in a given route.
3. Analogous to congestion indicators in wired networks, a novel solution using energy depletion indicators is used in conjunction with global thresholds to periodically reroute and balance energies.

Sensor nodes are assumed to be equipped with some localization hardware, such as a GPS (global positioning system) unit or a ranging device in order to be able to determine their geographic locations, as in [4]. We also assume that each node knows its neighbors' energy levels through periodic MAC layer broadcast. Therefore each node is capable of making a locally optimal greedy choice for the next-hop neighbor subject to global threshold values calculated efficiently in the mannner described later.

The steps of the threshold routing are as follows:

- Each data packet is marked by the source leader node with the geographical position of the destination node and with two threshold values min_{th} and max_{th}.
- Each sensor node receiving a data packet forwards it to that neighbor with energy level higher than min_{th} which is geographically closest to the destination.
- If all neighbors that are closer to the destination have energy level below min_{th}, i.e., when there is a hole, a node selects a neighbor whose energy level is highest above min_{th}. When there is no such neighbor, the node sends back the packet to its predecessor with a special message that the path is blocked. The predecessor node updates its routing table by placing the next best geographic neighbor as the next-hop and forwards the data packet to this neighbor. Note that there is a certain amount of backtracking involved which contributes to energy inefficiency. This is because we always to attempt to select the shortest path first. However by appropriate choice of parameters as described in section 3, the amount of backtracking can be reduced. Simulation results in Section 4 indicate protocol energy efficiency in spite of limited backtracking. Alternate protocol implementations without backtracking are possible as mentioned in Section 2.2.

- If the source receives a blocked data packet, this implies that a new threshold value min_{th} must be computed, as described in the next section.

Energy distribution across the sensornet changes over time as nodes deplete energy continuously. In order to find optimal paths consistent with the current energy distribution, threshold values must be recomputed periodically as described below:

- Each data packet contains a special n bit Energy Depletion Indicator (EDI) field, where $n \ll$ packet size.
- Each sensor node receiving a data packet determines whether its energy level is below another threshold max_{th}, a function of min_{th}.
- If the energy level of the node is below max_{th} and if the EDI field of n bits in the data packet is not exhausted, the node sets a single bit in the EDI field.
- If the receiver leader node gets a data packet with all n bits in the EDI field set to 1, it triggers a new selection procedure for min_{th}.
- Alternately, if the destination receives m data packets with at least one bit in the EDI field set to 1 a new selection procedure for min_{th} is triggered. Note that a single node on the current path with energy level below max_{th} continues to remain on the path until its energy level falls below min_{th} (At this point packets are rerouted around this node). We want new thresholds to be computed when multiple nodes *sequentially* fall below min_{th}(Note that this scenario is not captured by the previous EDI field algorithm). Let $k \ll m$ be the approximate number of transmitted packets required for a node's energy to fall from max_{th} to min_{th}. Choosing $m = kn$ will ensure that new thresholds will be computed in case of sequential energy depletions.

Note that the protocol as described above bounds the minimum energy level of any node from below by at most one packet transmission cost from min_{th}. As soon as a node's energy falls below this value it is cut off from participating until a new threshold is computed.

2.2 Minimum Threshold Function

The threshold routing protocol aims at finding the best path for data transmission. The threshold min_{th} should be such that it will force a packet to travel through one of the best or 'strongest' paths. While the strength of a path can be defined in various ways, not all of them can be easily computable. We introduce a simple notion of path strength whose main advantage is the ease of computation. We define *energy strength* of a path as the minimum residual energy among all nodes in the path. Therefore, the strongest path is the one whose energy strength is maximum.

Note that the above notion of energy strength implies that the threshold min_{th} must be chosen to be a fraction of the energy strength of the strongest path. Otherwise no path from source to destination with energy strength above the threshold value exists and therefore no threshold bounded routes can be formed. We formally define energy strength as follows: Let $\mathcal{P}$ be any path from the source to the destination and let E_i denote the energy level of the ith node on $\mathcal{P}$. Then, energy strength of path $\mathcal{P}$ is defined as:

$$E_s(\mathcal{P}) = min_{i \in \mathcal{P}}(E_i) \tag{1}$$

Let $\boldsymbol{P}$ be the set of all such paths. Then we have:

$$\max\_\min = \max_{\mathcal{P} \in \boldsymbol{P}}(\min_{i \in \mathcal{P}}(E_i)) \tag{2}$$

$$min_{th} = \alpha \times \max\_\min \tag{3}$$

where $0 < \alpha < 1$ is an 'inverse' density parameter that impacts the the set of feasible threshold bounded routes to the destination.

Similarly, the maximum threshold for appending bits is defined as:

$$max_{th} = min_{th} \times \rho \tag{4}$$

where $\rho > 1$.

Note that the proposed routing protocol emphasizes ***short yet energy-constrained paths*** by finding the geographically shortest path to the destination whose energy strength is *at least* min_{th}. While this path is not necessarily the strongest, the protocol can be easily modified to select strongest paths or in general, parameterized combinations of path strength and path length [9] by appropriately selecting next-hop neighbors during the max_min computation phase described below. In this paper, we focus only on the first approach.

2.3 Computation of max_min

We use a *directional flooding* technique to compute the value of max_min. The basic idea is to flood the network with control packets in the geographic direction of the source leader node. Note that the directional flooding occurs in the direction opposite to that of data transfer. The final value of max_min is determined at the sending leader node. The principal steps of the distributed max_min computation algorithm are as follows:

- The destination leader node floods the network with control packets along the geographic direction of the source leader node as explained below.
- Each node forwards *exactly* one control packet to all its neighbors in the geographic direction of the source leader node. 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.
- On receiving the first control packet, each node checks whether its timer is set. If the timer is not already set, it sets the timer for a prefixed interval. 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 and when the timer expires, the node updates and stores the highest EM_p value seen so far in received control packets if its own energy level E_i is higher than all of them. Otherwise, it stores its own current energy level E_i.
- When the timer expires, this node forwards a new control packet with EM_p field set to the stored energy strength value to all its neighbors in the geographic direction of the source leader node. Control packets arriving after the timer expires are discarded.
- Eventually, the source leader node begins receiving control packets with energy strength values. The source leader node also sets its timer on for a prefixed time period T in order to receive packets from most of its neighbors. Value of T can be determined in many ways depending on specific requirements of applications. In this paper, we calculate T to ensure that most of the paths from the source leader node to the destination leader node are included in the optimality calculations. If the maximum transmission delay between two nodes is D_{max}, then the value of T is determined as $MINHOP \times D_{max}$, where $MINHOP$ is an estimate of the shortest path from the source to the destination leader node. This value can be estimated apriori using GPSR routing[5] before the first data transmission phase. Note that the given value of T allows control packets from paths upto twice the length of the shortest path to be forwarded to the source leader node. Also note that D_{max} is a function of the specific MAC-layer protocol being implemented in the sensor network. When the timer expires, it selects the final max_min value and sets the two thresholds accordingly. The flooding phase ends here and the normal data transmission phase resumes with new threshold values.

3 Selection of Parameters

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

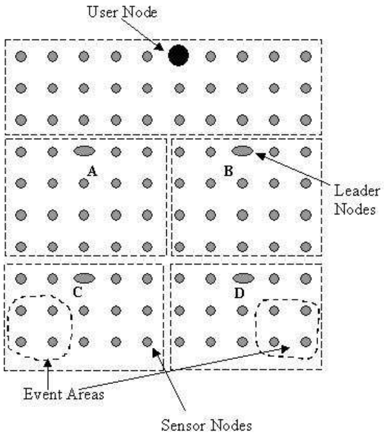

Figure 1: Simulation topology.

- To avert unnecessary wastage of energy, it is necessary to prevent control packets from hanging around the network after the path determination phase. The parameter MINHOP serves this purpose.
- Clearly, 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 these parameters using α, ρ and EDI as described later.

3.1 Selection of α and ρ

The value of min_{th} is proportional to α. Lower values of α will increase the number of feasible paths from source to destination leader nodes. However, this will also undesirably increase the number of energy deficient nodes participating in routes. Therefore, a careful selection of α is important. Similarly ρ and the length of the EDI field control the duration of data transmission, since reverse directional flooding starts when the residual energy levels of at least EDI number of nodes participating in the path fall below threshold max_{th}. α and ρ are empirical values and should be experimentally determined using observed energy depletion rates and traffic patterns.

3.2 Overhead Due to Reverse Flooding

The proposed protocol uses reverse directional flooding to determine a new optimal path. The advantage of using directional flooding over general flooding is that packets being forwarded only in a single direction produces less overhead. The following proposition gives an estimate of the overhead due to directional flooding in terms of number of control packets.

Proposition 1:*In a geographically routed wireless sensor network with arbitrary topology and V nodes participating in the reverse flooding phase, exactly V control packets are transmitted.*

Note that V, the number of nodes particpating in reverse flooding is expected to be $\ll N$, the total number of sensor nodes in the network. During the reverse flooding phase, at each node, only one packet becomes the winner among all the packets received by the node from its neighbors. All other packets are discarded. Each node then broadcasts the same packet to all of its neighbors that are in the geographic direction of the source leader node. Thus, a total of V nodes will send at most V broadcast packets.

4 Performance Evaluation

We proposed our threshold constrained geographic routing protocol (TCGR) with the goal of balancing energy consumption uniformly over all the nodes of the network. Therefore, we use the following metrics for

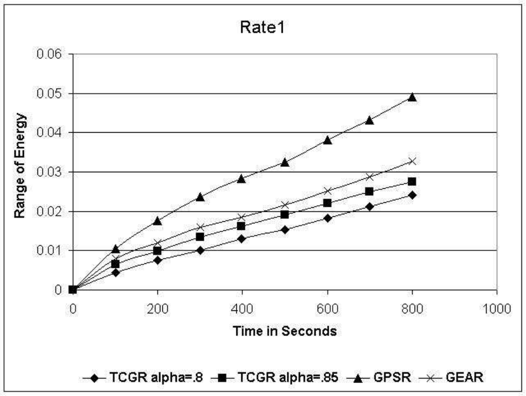

Figure 2: Range in residual energy levels across the network under TCGR with $\alpha = 0.8$, $\alpha = 0.85$, GPSR and GEAR at traffic rate 1.

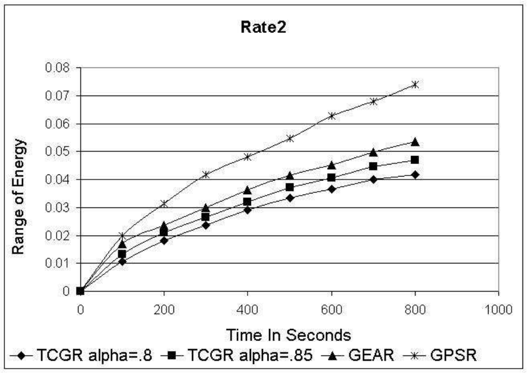

Figure 3: Range in residual energy levels across the network under TCGR with $\alpha = 0.8$, $\alpha = 0.85$, GPSR and GEAR at traffic rate 2.

performance evaluation which can also serve as an indication of the network lifetime.

- **Variance of energy**: This metric measures the variance of the energy levels of all the nodes. 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.

4.1 Experimental Setup

These experiments are carried out on our simulation test-bed which is an extension of Sensorsim [10]. We modified the routing layer of the simulator to test our routing protocol. The main role of our routing layer is to route the normal data packets using TCGR and also to do the reverse flooding for the computation of max_min.

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. We have four leader nodes in the network as shown in Figure 1. Sensor nodes in event areas capture events and generate packets that are transmitted to their corresponding leader nodes C and D. Then, nodes C and D send packets to B and A respectively using TCGR. A and B forward packets to the user node using TCGR. The intermediate sensor nodes are responsible for routing these packets between the source and the destination leader nodes. A destination leader node initiates the reverse flooding when

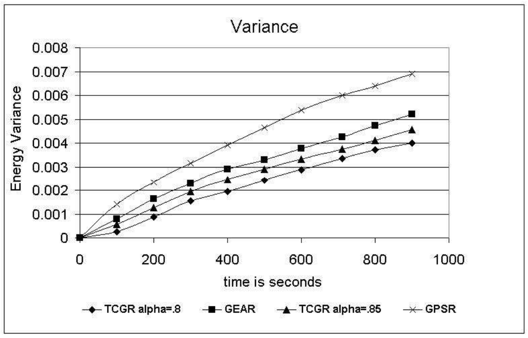

Figure 4: Variance in residual energy levels across the network under TCGR with $\alpha = 0.8, \alpha = 0.85$, GPSR and GEAR.

it receives a sensor data packet indicating that at least 3 (EDI field value) sensor nodes are close to the threshold min_{th}. The sender leader node sets a new min_{th} as described earlier. Note that the user node can also initiate the reverse flooding mechanishm. We fixed the values of α and ρ as constants in our simulation. We ran the simulation for 1000 seconds with three routing protocols: simple GPSR, GEAR and the proposed threshold bounded routing protocol.

We tested the performance of our protocol under two traffic rates. In our simulation we used a broadcast TDMA-based MAC layer protocol [10]. In our first traffic rate rate1, a packet is generated every three TDMA frames. While simulating using rate2 a packet is generated every two frames.

In Figures 2 and 3, we present the range of node energy distributions ober time across the network under the three protocols. Our protocol is expected to result in lower range of energy distributions since threshold routing balances energy loads. Figures 2 and 3 show that rate of increase of range of energy is much lower in our protocol than in GPSR and GEAR. As time proceeds, range in GPSR increases at a higher rate indicating a much shorter network lifetime. A higher range is due to the fact that some nodes are treated unfairly while other nodes do not participate in routing. Our protocol yields better range of energy levels than GEAR. This is beacause GEAR is a predominantly local algorithm whereas our protocol uses limited global information in making local decisions.

Figure 4 represents the variance of energy distribution in the network. The energy range metric does not measure the number of sensor nodes that are being treated unfairly. The higher variance of GPSR and GEAR 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.

Figure 5 shows the energy of the minimum energy level node in the network produced by TCGR,GPSR and GEAR with time. Using a higher value of α causes the route to be changed more frequently than required. This is why the minimum energy level is more for the case when α equals .8. The value of α should be tuned appropriately to get maximum performance gains from our protocol.

5 Conclusion

We have proposed a distributed routing protocol which uses threshold energy level and determines an energy constrained geographic route. This protocol attempts to balance the energy consumption over the whole network and to increase network lifetime. A performance evaluation has been done using ns-2 simulator. Our simulation results indicate that using the proposed balanced energy routing protocol results in much higher residual node energy levels over time as opposed to GPSR and GEAR. Range and variance of node energy distribution across the network are also significantly lower than that achieved with GPSR and GEAR.

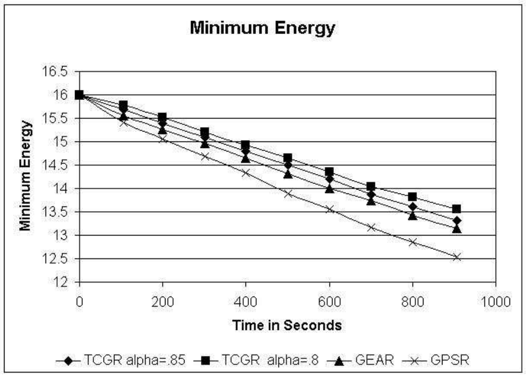

Figure 5: Minimum residual energy levels across the network with TCGR, GPSR and GEAR.

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