Delay Differentiation in Sensor Networks using Power Control

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***Abstract*— In a heterogeneous ad-hoc sensor network, diverse information with different priority are sensed and relayed between the sensor nodes. Moreover, delays in an ad-hoc network can be large either due to the multi-hop nature of the network or due to aggregation delays at intermediate nodes. In this paper we develop a framework to provide delay differentiation among several data types by associating a power budget with every data packet. The power budget of a message limits the overall excess power that can be used by all intermediate nodes to transmit this packet. We first consider a grid placement of nodes to derive an optimal solution by an integer program to this problem. Then we solve the same optimization problem for an arbitrary placement of nodes on a plane. We then propose a decentralized and randomized algorithm that approximates the optimal solution. The decentralized solution is then compared to the optimal solution using simulations.**

I. INTRODUCTION

A heterogeneous wireless sensor network consists of heterogeneous sensors sensing and relaying diverse information about the environment. For example, a sensor network might be employed to monitor the environment of a particular area. Such networks might collect information about the temperature, pressure and seismic activity of the area being monitored. As a result, some information has higher priority than other information. For example, in the environment sensor network, data about seismic activities are much more delay sensitive than data about temperature. As a result, one needs to differentiate among these diverse sets of data when transmitting and relaying information. A framework for providing differentiation among data of different types over sensor networks is missing. In an ad-hoc network, delays can be large either due to the multi-hop nature of the network or due to aggregation delays at intermediate nodes. The multi-hop nature of the network arises due to the fact that such networks are designed with the objective of either maximizing the overall throughput of the network or maximizing the lifetime of the network (as in a sensor network). As a result, short links are preferred over longer links and energy-efficient routing results in a non-optimal route from a delay perspective. Aggregation delays arise due to the fact that intermediate nodes tend to aggregate data before relaying to maximize the lifetime of the network. Such approaches result in large delays when transmitting high priority data or sensitive information.

Delays in ad-hoc networks can be controlled using the transmission power of the nodes. A higher transmission power at the nodes has two main ramifications: 1) It causes interference in a larger neighborhood and hence limits the overall throughput of the network and 2) It results in a faster drain of the power source (due to increased transmit power and possible retransmissions due to contention) thereby reducing the lifetime of the network. Hence a tradeoff between delay, throughput and lifetime exists. In a sensor network, the throughput of the entire network is not a critical performance measure as the load on a sensor network is not high. As a result, we believe that while scheduling high priority data, the cost incurred on the lifetime of a node due to the higher transmission power dominates other costs. Understanding this tradeoff is critical to the successful deployment of sensor networks in missions of critical nature.

In this paper we propose a framework to provide differentiated services over a sensor network by associating power with priority. We assume a underlying routing structure that is derived using any of the various energy-efficient routing schemes [6], [13], [4]. All data packets are routed by default using this routing scheme. In addition to this routing, we now associate a power budget with each data packet at the source. The power budget indicates the total excess power that can be used by all nodes (in its path) to transmit this packet. By excess power, we refer to the difference in the power consumption if the packet follows any other route other than the energy-efficient route. Higher the power budget of a packer, greater its priority. The nodes can transmit this data packet with a higher power (assuming its power constraints allow it to do so) provided the total excess power that is consumed does not exceed the power budget of the packet. Therefore, greater the power budget, lower the delay incurred by the packet. In this paper we propose such a scheme to provide differentiated services and present preliminary results about the scheme.

The paper is organized as follows: we discuss related work in minimum energy routing and Quality of Service (QoS) in ad-hoc networks in Section I-A. We describe the system model in Section II and discuss a centralized solution in Section II-A. We the provide a decentralized solution to the differentiated services problem in Section IV and discuss some preliminary simulations in Section V.We finally conclude in Section VI.

A. Related Work

Different metrics for power-aware routing such as energy consumed per packet, time to network partition, variance in node power levels, etc have been suggested in [13]. An energy conserving routing scheme where routes are selected based on the current power levels of the nodes has been proposed in [6]. They also show that for maximum lifetime, messages must be routed such that energy consumption amongst nodes is balanced in proportion to their remaining energy. Alternatively the underlying routing scheme may also be designed to maximize the total number of messages sent over the network as shown in [9]. A routing scheme based on energy drain rates of nodes is proposed in [4]. A variant of their scheme chooses a rate based on the residual energy of nodes and the minimal drain rate of nodes (which is periodically updated) if it is beyond a preset threshold. Otherwise routing is normally done so as to minimize total transmission power [10].

A distributed routing algorithm for ad-hoc networks called CEDAR was proposed in [14]. The key components of their algorithm were a self maintaining network core to compute routes based on the state of links which is propagated through the network and a QoS route computation algorithm that decides the route based on information available locally. Another distributed QoS routing protocol for ad-hoc networks was proposed in [3]. Based on the required bandwidth or delay, multiple paths are computed and a route is then chosen. QoS provisioning based on call admission control in which the nodes query the network for resources has been proposed in [11].

QoS may also be made available by modifications at the Medium Access Control (MAC) layer [7]. The authors propose that high priority nodes use short high energy pulses (black-bursts) to jam the channel and then gain access to the medium. Higher the priority longer the jamming period. The authors go on to show that after the initial period of jamming, nodes get synchronized to have a prioritized scheduling. However this work is designed towards for QoS in ad-hoc networks like Wireless Local Area Networks (WLANs) and not for stand-alone networks that are power constrained like sensor networks. Our proposed algorithm is complementary to these approaches and is designed specifically for sensor networks. It works to build on existing routing algorithms based on energy efficiency and provide delay differentiation with low cost routes.

II. SYSTEM MODEL

Consider a wireless ad-hoc sensor network in which the nodes are capable of transmitting at different power levels. We will assume an underlying routing infrastructure which is designed to maximize the lifetime of the network. By default all packets will be routed using such routes. In addition, each data packet is associated with an excess power budget which specifies the maximum excess power that can be used in the transmission of this packet. The power budget is set by the source depending upon the priority of that packet. Setting of this power budget is a subject of ongoing research and is beyond the scope of this paper. In this paper we will assume that the budget has been set by the source. The intermediate nodes can transmit this packet with a higher power as long as the excess power consumed does not exceed the power budget. The remaining power budget of the packet is updated whenever a node uses a higher transmission power to transmit the packet. The excess power used at each step is subtracted from the message's budget. Since the total flow of data is low in a sensor network, we assume the degradation in throughput caused by the excess interference is minimal.

We illustrate the concept of power budgets using the following example. Consider the placement of sensors in a grid as shown in Figure 1. The source and destination nodes are shown in the figure. We also assume that the power required to transmit to a node d units apart is proportional to d^2. Without loss of generality, normalize the transmission powers such that a unit of power is required to transmit successfully to a neighboring node along the x-axis or y-axis. Assume that each node can transmit up to a power level (normalized) of 5. Without any data differentiation, a packet from the source to the destination would follow the low-energy path (that is obtained as a solution to the network lifetime maximization problem) given by:

$$S \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow D \tag{1}$$

resulting in 6 hops. Now assume that the packet is associated with a power budget of 1. In this case, the maximum excess power that can be expended by the network towards the delivery of this packet is 1 unit. In this case, the data packet can follow the path

$$S \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow D \tag{2}$$

resulting in 5 hops. Note that 2 units of (normalized) power are required at node S to transmit to node 2. Therefore at node S, the excess power used is equal to 1 units. Hence the remaining power budget of the data packet is set to zero. This ensures that none of the downstream nodes will use any excess power to transmit this data packet. Also note that even though the total power consumed by the route given in (2) is equal to the total power consumed by the route in (1), the latter route is preferred for low-priority packets since it distributes the energy usage among more nodes thereby extending the network lifetime. If the power budget of a packet is 3, then the message can follow the route

$$S \rightarrow 2 \rightarrow 4 \rightarrow D \tag{3}$$

resulting in 3 hops. If the power budget of the packet is 10 units, then the data packet can use the path $S \rightarrow 3 \rightarrow D$ which results only in two hops. The power budget at node S is updated to 6 units since 4 units of power are used by node S to transmit to node 3. Similarly, at node 3, the power budget of the data packet is set to 2 units.

Note that with a power budget of five, the message can follow either

$$S \rightarrow 3 \rightarrow 6 \rightarrow D \tag{4}$$

resulting in 3 hops and use all the excess budget or it can follow the path given in (3) which also results in 3 hops but consumes much lower power. The problem then is to determine the optimal distribution of the budget such that the message is routed from source to destination with minimum number of hops and satisfies the constraint on the excess budget. We will consider this problem in two different

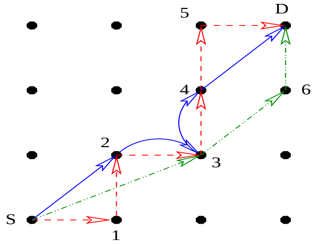

Fig. 1. *Example illustrating the role of power budgets in routing*

scenarios: one where all the nodes are placed along a grid and a more general case where the nodes can be placed arbitrarily on a plane. For the case when the nodes are placed on a grid, we formulate the problem of finding the optimal distribution of the budget as an Integer Linear Program (ILP). For the general case, we provide a probabilistic algorithm that determines the transmission power based on the budget and evaluate its performance using simulations.

A. Sensor Grids

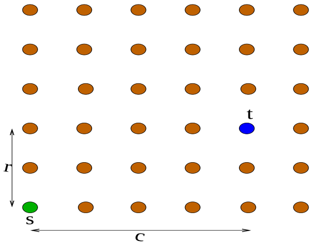

Fig. 2. *Nodes placed on a grid.Source s and destination t are separated by r rows and c columns*

Consider sensor nodes placed on a square grid of size $n \times n$ as shown in Figure 2. Without loss of generality, we will assume that the distance between two sensor nodes is 1 unit. We will assume that a transmission power of $p(d)$ is required to transmit a message to a node at a Euclidean distance d units away. Without loss of generality, normalize the power required to transmit a message successfully to a neighboring node (which is unit distance away) to be $\hat{p}$.

Let the source s and destination t be separated by r rows and c columns. Given the source and destination, one can easily find a minimum energy route for the grid network. For the sake of exposition, let $c > r$ as shown in Figure 2. The minimum power required to transmit a message is given by $(c+r)\hat{p}$. Let P be the excess budget that is allocated to message M.[1] We wish to find the minimum hop route that such that total excess power that is used at all the intermediate nodes is less than P.

Let x_{ij} be the number of hops that traverse i rows and j columns. We can now write the optimization problem as:

$$\begin{aligned} \min\ & \sum_{\forall(i,j)} x_{ij} \\ \text{subject to}\ & \sum_{\forall(i,j)} j.x_{ij} = c \\ & \sum_{\forall(i,j)} i.x_{ij} = r \\ & \sum_{\forall(i,j)} (p(\sqrt{i^2+j^2}) - \hat{p})x_{ij} \le P \\ & x_{ij} = 0,1,2,3,\ldots \qquad \forall i,j \end{aligned} \tag{5}$$

The objective here is to minimize the delay i.e. number of hops from the source to destination. The first two constraints ensure that the message reaches the destination and the third constraint ensures that the excess power used at each stage is less than the allocated budget. Note that the excess power at each node is the extra power that the node uses to transmit at a higher power. The variables here can take only non-negative integral values.

Proposition II.1 *The solution of the Integer Program in (5) gives the minimum number of hops that can be achieved with a power budget of* P. ■

It is easy to see that the Integer Program in (5) may have multiple optimal solutions. However, the optimal solutions may differ in the total power consumed for transmitting the packet between the source and destination. For example, in Figure 1 with a power budget of five, both (2) and (4) are solutions to the Integer Program. However, the route in (2) has a much lower power consumption than the route in (4). In order to obtain minimum number of hops and use the minimum possible budget, the Integer Program in (5) can rewritten as:

$$\begin{aligned} \min\ & \sum_{\forall(i,j)} Kx_{ij} + \sum_{\forall(i,j)} (p(\sqrt{i^2+j^2}) - \hat{p})x_{ij} \\ \text{subject to}\ & \sum_{\forall(i,j)} j.x_{ij} = c \\ & \sum_{\forall(i,j)} i.x_{ij} = r \\ & \sum_{\forall(i,j)} p(\sqrt{i^2+j^2}) - \hat{p})x_{ij} \le P \\ & x_{ij} = 0,1,2,3,\ldots \qquad \forall i,j, \end{aligned} \tag{6}$$

where K is a suitable large constant.

Proposition II.2 *The optimal solution to the Integer Program in (6) provides the minimum number of hops with the least consumption of the power budget.*

Proof is not included here due to space constraints. The interested reader is referred to [12].

Note that the Integer Program in (6) can have multiple optimal solutions that gives the same hop count and same power consumption. That is, there may exist multiple routes with the same hop count and same power consumption. Here the final choice on the which of these optimal routes is to be

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[1] One can also consider a similar formulation for a flow instead of a message.

used can be based on different factors like remaining power level at the nodes, the route that would require the least rescheduling of other messages, the route that offers more uniform distribution of power and hence a better lifetime of the network. Another important factor that should be considered is that the next hop selected should provide better opportunities for optimal utilization of power. These issues are topics of current research and beyond the scope of this paper.

III. NODES PLACED ARBITRARILY ON A PLANE

Consider a sensor network in which the nodes are placed arbitrarily placed on a plane. As in the previous section we associate a power budget with each packet that specifies the maximum excess power that can be used to transmit the packet from the source to the destination. Construct a graph $G(V, E)$ where V is set of all nodes in the network and E is the set of all allowed links between nodes. We assume that each node can transmit with multiple power levels and that the graph is connected when all nodes use the lowest power level for transmission. The cost of an edge is the transmission power required for successful reception. We normalize the cost of each edge such that the cost of the edge that requires the lowest power has a cost of zero. In other words, the cost of an edge (i, j) is equal to the excess power that is required to communicate to node j from node i. The question we wish to answer is: *What is the shortest path in terms of number of hops from a given source to a destination such that the cost of the path is less than the power budget P?*

The problem of finding the minimum number of hops within the power budget can be solved by the Bellman Ford algorithm. The Bellman-Ford algorithm works as follows. Let D_i^h be the optimal (minimum) cost of the walk from node i to destination t with at most h hops. Initialize:

$$\begin{aligned} D_t^h &= 0 \qquad \forall\ h \qquad \text{and} \\ D_i^0 &= \infty \qquad \forall\ i \neq t. \end{aligned}$$

The shortest paths are now updated using the following algorithm:

$$D_i^{h+1} = \min_j [c_{ij} + D_i^h].$$

The proof that this update algorithm gives the optimal path using at most h hops can be found in [2]. Now to achieve our objective we start the Bellman-Ford algorithm at each node and run one iteration. At the end of this iteration we check if the destination can be reached from a given source node at a cost less than the allocated budget of that message. If not we continue successive iterations until the cost of the path satisfies our requirement.

Proposition III.1 *The solution given by the above algorithm achieves*

1) *minimum possible number of hops*
2) *minimum power amongst all solutions that require the minimum number of hops.*

The interested reader is referred to [12].

IV. DECENTRALIZED SOLUTION

It is important to note that in the previous section the optimal solution was derived with complete knowledge of the distance between the source and destination and position of all nodes. In the situation where the nodes do not know the exact distance to the destination but only have routing tables to give the next hop for different power levels the problem becomes much more hard. This problem of optimal distribution of power along the path from source to destination is difficult as without knowledge of the position of the nodes and total distance to the destination, the optimization constraints cannot be specified properly. We propose to lower the delays by using a randomized approach as described below.

A. Sensory grids

In this section we assume that the nodes are placed on a grid and that each node has a routing table for different power levels. For the example shown in Figure 1 the source S has a routing table for destination D indicating that for a normalized power level $p_S = 2$, the next hop neighbor is node 2; if the normalized power level $p_S = 5$, the next hop neighbor is node 3. Initially the source S chooses a random power p_1 uniformly between 0 and P and transmits the message to corresponding next-hop as indicated in the routing table with that power (or the lower power level closest to it). Before transmission, the budget P of message M is updated to $P - p_1$. Note that the distribution of the transmission power choice can depend on various factors like remaining power at the node and the number of hops to the destination. The choice of this distribution is a subject of future research. The next node on the path (say, node 1), chooses a power p_2 uniformly in $[0, (P - p_1)]$ and correspondingly updates the budget for message M. Note that the above approach can be easily extended to a situation in which the nodes are not placed on a grid as in the example above. This is discussed further in section IV-B.

B. Nodes placed arbitrarily on a plane

We have seen centralized and decentralized approaches for implementing introducing delay differentiation in a network of nodes placed on a grid in sections II-A and IV-A. The approach proposed in III can be used to obtain the centralized solution for a network where nodes are placed arbitrarily on a plane. However, we would like a decentralized solution for such a network. But if each node along the path independently chooses a transmission power then we are immediately faced with the possibility of loops in routing. In [8] the authors propose a solution that the path must be chosen with non-increasing powers to avoid loops. We propose a different method to avoid loops. The decentralized solution proposed in Section IV can be used with some modifications. We assume here that routing tables are computed for transmissions using various power levels and are available at each node. For example, the routing table of a node A will say that it can reach node D using power level #1 for all transmissions in 5 hops , 4 hops using power level #2 for all transmissions

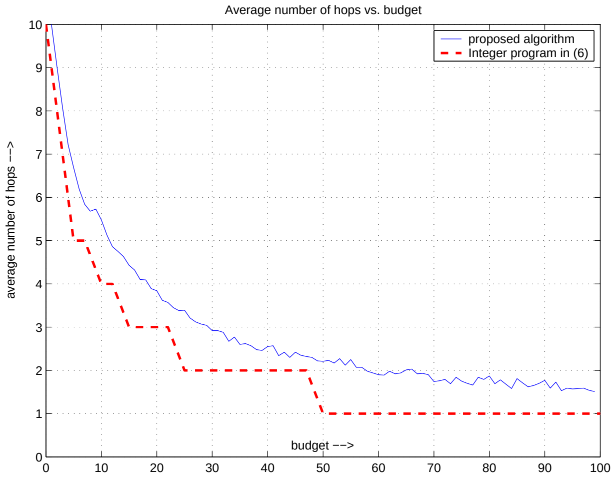

Fig. 3. *Average number of hops vs. allocated budget using proposed random power algorithm and the optimal solution given by the Integer Program for a source-destination pair separated by 5 rows and 5 columns*

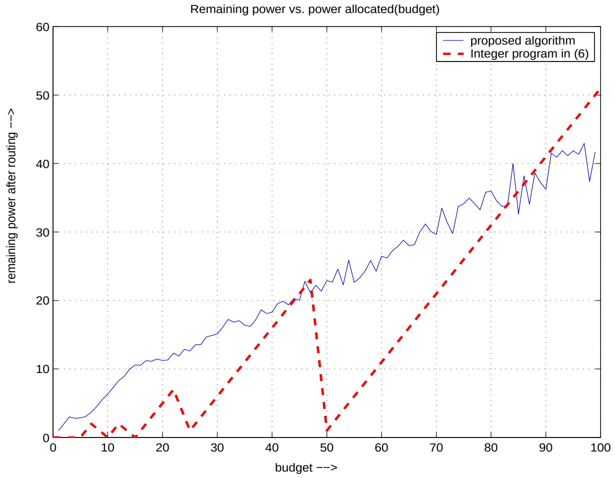

Fig. 4. *Remaining power vs. allocated budget using proposed random power algorithm and the optimal solution for a source-destination pair separated by 5 rows and 5 columns*

, 2 hops using power level #3 for all transmissions and so forth indicating next hops for each power level as computed by any routing algorithm. Also we assume that these routes at individual power levels do not have any loops.

As in the earlier algorithm in Section IV-A, each node along the path will choose a power at random based on the budget of the message. However before transmitting at a higher power each node checks to see if the number of hops from the node chosen as next hop (based on the randomly chosen power level and the routing table) at the lowest power level is less than the number of hops at the current node by at least 2 hops. If not it transmits at the lowest power. Also if node can reach another node at more than one power level, it always uses the lowest power level. The intuition behind this algorithm is that higher power is used only if the number of hops can be reduced by at least 1 hop.

Proposition IV.1 *The algorithm described above avoids any loops.*

The interested reader is referred to [12] for the proof.

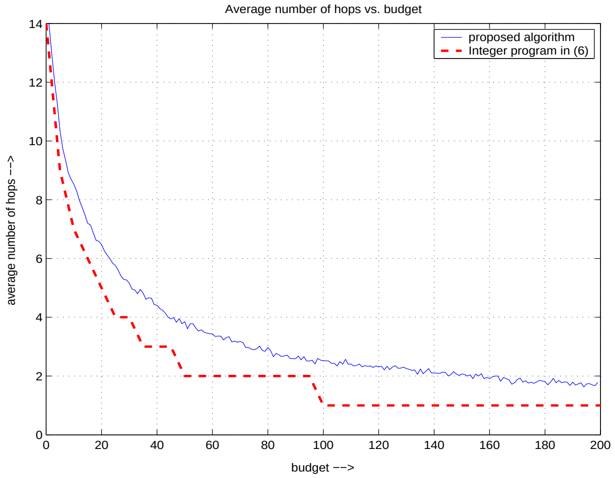

Fig. 5. *Average number of hops vs. allocated budget using proposed random power algorithm and the optimal solution given by the Integer Program for a source-destination pair separated by 8 rows and 6 columns*

V. SIMULATIONS

We assume a grid of size 10×10. The source and destination nodes are picked up randomly. The normalized power required to transmit one hop along the x-axis or y-axis is one unit. The different power levels are set to the powers required to reach different nodes on the grid. For example a normalized power of 2 is required for one hop along the diagonal, a power of 4 is required for reaching a node 2 units away on the x-axis or y-axis. Thus the different power levels are $1,2,4,5,8,\ldots,2n^2$. Note that with a sufficient budget the source may be able to reach the destination in one hop.

In the first experiment the source and destination pairs are picked randomly such that they are separated by 5 rows and 5 columns. So with no additional budget the message would require at least 10 hops to reach the destination. We then compute the optimal number of hops and power required for varying budgets. For the source destination pair we then route messages with a similar budgets using the randomized scheme described in IV. It is assumed that all nodes have enough power to transmit the message with the randomly chosen power. We then compare the performance of the performances of the randomized algorithm and the optimal solution obtained from the Integer Program in (6). We use the software LP-Solve [1] to obtain the number of hops with optimal power distribution. In Figure 3, we compare the two solutions with respect to the average number of hops obtained for a power budget.From Figure 3 we can see that as the allocated power budget increases, the number of hops required to transmit

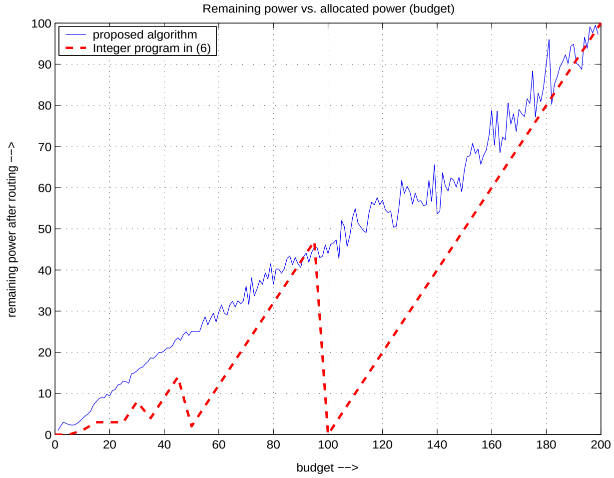

Fig. 6. *Remaining power vs. allocated budget using proposed random power algorithm and the optimal solution for a source-destination pair separated by 8 rows and 6 columns*

the message from the source to the destination reduces. We observe that the performance of the proposed randomized algorithm is close to the optimal solution.

Since our scheme for the decentralized solution uniformly chooses a random power, all of the allocated budget may not be completely utilized. Figure 4 shows the unutilized power budget after the message is routed using the optimal solution and using our proposed algorithm. Note, in simulations for our proposed algorithm the budget is incremented by 1 for each simulation while the Integer Program is solved for budgets increasing in steps of 2 or 5 units. We can also observe (from the sudden drops) that the solution to the Integer Program in (6) chooses the minimum energy path amongst all possible paths of minimum hop length, so any excess energy is unutilized if it is not able to reduce the number of hops any further.

Figure 5 also compares the proposed randomized algorithm in Section IV with the optimal solution in Section II-A when the randomly chosen source destination pair is separated by 8 rows and 6 columns. We can see that the performance of the randomized algorithm is close to the optimal solution. The unutilized power budget after the message is routed using the centralized solution given by the Integer Program and using our proposed algorithm are shown in Figure 6.

VI. Conclusions and Ongoing Work

In this paper, we discussed a framework to provide delay differentiation in sensor networks by associating a power budget with each message. Given a power budget and a source-destination pair, we formulated the problem of finding the minimum hop route that satisfies the power budget constraints. We then proposed a randomized algorithm to approximate this optimal solution. The results can be easily extended to multiple source destination pairs by using a multi-commodity version of our Integer Program.

In the model considered in this paper, nodes are assumed to be able to communicate at multiple power levels and store routing information corresponding to each of these power levels. However, due to the limitations on memory and power consumption, we believe that using just two power levels, LOW and HIGH would strike a compromise between complexity and ability to provide delay differentiation. Since our proposed solutions to the problem is designed for multiple power levels, the same may be used for just two power levels LOW and HIGH. The LOW power must be set to the minimum power required to maintain connectivity [8]. However, the HIGH power level would lead to higher interference and hence affect the throughput of the network [5]. The choice of the HIGH power level is a subject for future research.

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