ENERGY BALANCED COMMUNICATION IN WIRELESS SENSOR NETWORKS

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We propose threshold randomized routing (TRR) in multi-hop wireless sensor networks as a strategy for structured communication that provides a *tradeoff among total energy consumption, total latency, and energy balance.* Energy balance is a special concern because the collaborative nature of sensor network applications can render an energy-constrained sensor network useless if energy imbalance leads to a network partition. We evaluate the effectiveness of this strategy for worst-case and average-case permutation routing scenarios for a range of network sizes. This work is part of our effort to define a hierarchical methodology for application development for wireless sensor networks, based on energy-efficient communication and computation primitives that hide networking details from the application developer.

1 Introduction

Wireless sensor networks (WSNs) are typically designed and optimized for a specific application that is known at design time. Due to the limited energy supplies available to individual sensor nodes, the major challenge facing the designer is to maximize the lifetime of the network through energy-efficient implementation of communication patterns known *a priori*[a]. In addition to the total energy consumed by a particular (collaborative) task, energy balance is also a critical measure of energy efficiency. Intuitively, energy balanced implementations will maximize the time to network partition, which is one of the measures of system lifetime.

This paper deals with structured communication, i.e., routing problems where the communication pattern is known in advance. Unlike the Internet, where point-to-point communication is the basic primitive, the collaborative nature of communication and computation in WSNs makes structured communication relevant. Example primitives are one-to-all, all-to-one, many-to-many, permutation, etc. We propose and evaluate *threshold randomized routing* (TRR) as a general routing strategy that provides a smooth tradeoff between latency, energy, and energy balance. Although we simulate multi-hop mesh topologies for simplicity, the routing technique itself is not restricted to a particular topology.

In 1-1 permutation routing, each node transmits one packet to some other node and expects to receive one packet. Energy-efficient permutation routing in single-hop wireless networks has been the subject of recent research[3]; here we compare energy-balanced routing mechanisms for permutation routing in multi-hop networks. *Matrix transpose* is a pathological case of permutation routing in terms of network congestion and the corresponding impact on latency. In addition, naive shortest-path routing for matrix transpose leads to a severe energy imbalance in the network. Matrix transpose is interesting from a purely theoretical perspective because its extremal behavior makes it a benchmark to evaluate efficient permutation routing schemes. In terms of sensor network applications, matrix transpose is a core operation in distributed digital signal processing such as multidimensional FFT. An efficient implementation of matrix transpose could improve the performance of *collaborative signal processing* kernels for wireless sensor networks[4].

The remainder of this paper briefly describes our system model, introduces threshold randomized routing, and evaluates its performance for two different permutation routing patterns that represent the worst-case and average-case performance respectively of greedy routing strategies.

2 System Model

We consider a homogeneous wireless sensor network, where each node is equipped with one radio with omnidirectional antenna. The radio can be in the Transmit, Receive, or ShutDown state. Energy consump-

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[a] Computation issues are not addressed in this paper

tion is same for the Transmit and Receive states; and zero (negligible) for ShutDown. The n^2 nodes in the network are distributed uniformly over a square 2D terrain. The terrain can be modeled as n^2 cells of unit size, with one node in each cell. Each node is identified by its row and column number; node in row i and column j is labeled (i, j), where $0 \leq i, j \leq n-1$. A node can communicate only with its four neighbors. All data is exchanged in fixed size packets with unicast addressing. A CSMA/CA mechanism with RTS/CTS signaling is used for channel access. The time (energy) for transfer of a data packet is d times the time (energy) for resolving contention over the channel, i.e., for transferring an RTS/CTS packet.

3 Routing Strategies in Multi-Hop Networks

Greedy Routing: Most routing protocols in multi-hop networks implement some variation of the greedy shortest path algorithm, which we consider the de facto baseline. For our simulated mesh topology, we use the well-known *XY routing* as the greedy routing algorithm. Each packet travels along the X dimension (row) till the destination column is reached and then along the Y dimension (column) till the destination node is reached.

Greedy algorithms are attractive because they are very simple to implement, rely solely on local decisions and require negligible state[b] per node for routing. For one-to-one routing problems, greedy algorithms perform very well in the average case and very poorly in the worst case[2] in terms of total latency. Since each packet takes the shortest path, the total energy of routing (ignoring contention) is also minimum for the greedy approach. In XY routing for matrix transpose however, all data items in a row move to the corresponding column. This causes *congestion* along the diagonals, which leads to worsening latencies as the network size increases. Of greater concern in the context of energy-constrained sensor networks is that *XY routing is not energy balanced* for patterns such as matrix transpose because heavily loaded diagonal nodes could lead to a network partition.

Randomized Routing: In the basic *two-phase randomized routing* technique proposed in [5], each packet in the network is initially sent to a random destination within the network and then to its correct destination. Each phase could use greedy routing. Randomized routing is known to be useful in reducing total latency of worst-case problems such as transpose[2], because the elements along a row are not held up waiting for the preceding elements to move one by one via the diagonal element. However, since randomized routing really converts the routing problem into two sub-problems, it could take twice as much time as greedy routing on average. Since randomization disperses the paths throughout the network, *energy balance* improves. Unfortunately, dispersing the routes through the network also causes packets to take longer paths to their destinations, thereby *increasing the total energy.*

4 Threshold Randomized Routing

Threshold randomized routing (TRR) is motivated by the need to achieve a *tradeoff between latency, energy, and energy balance.* Energy overhead for a given packet under randomized routing can be defined as the ratio of the increase in path length to the shortest path between the source and destination of that packet. Intuitively, the energy overhead with randomized routing (on average) is inversely proportional to the length of the shortest path between the source and destination. If the destination is 'close' to the source, randomized routing might not be desirable because of the energy and latency overhead, even if energy balance is achieved. On the other hand, if the destination is 'far' from the source, randomized routing will not cause much overhead, while still balancing the energy dissipation and possibly reducing the latency in worst-case scenarios.

In TRR, the packet is routed greedily if the shortest path between source and destination is less than a user-specified threshold, and randomly (two-phase) otherwise. The threshold can be tuned to obtain a smooth tradeoff between total latency, total energy, and energy balance. Decreasing the threshold will typically improve the energy balance and increase the total energy. The latency could increase or decrease, depending on the routing problem. Due to space limitations, we discuss the application of TRR only for two patterns: *matrix transpose* and *row shuffle.* Matrix transpose is the worst-case (latency)

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[b] We assume that each node knows its position in the mesh.

scenario for permutation routing. The row shuffle pattern is an average case scenario, where node (i, j) sends a packet to node $(i, n-1-j)$.

Figures 1(a) and (b) illustrate TRR for these two patterns. For matrix transpose, the diagonal elements are most heavily loaded, and for row shuffle, the elements in column $\frac{n}{2}$ are the most heavily loaded. Therefore, a threshold of k results in the routing zones as shown in the figures. $k = 0$ represents complete randomized routing.

TRR might not be very useful if every node in the network is both a source and a destination of packets, e.g., in matrix transpose, the total number of packets that cross the diagonal are the same, regardless of how each packet is routed. TRR does reduce latency but energy balance is achieved not by reducing the load on the diagonals, but by increasing the load on non-diagonal elements. TRR will be of greater use if energy balance can be achieved by recruiting nodes that will otherwise not participate in the routing problem at all. For example, if the only activity in the network is node $(0, 0)$ periodically sending packets to node $(n-1, n-1)$, greedy routing will cause a network partition. If TRR is used, the routes will be distributed throughout the network, thereby improving energy balance. Fortunately, for sensor network deployments with low duty cycles where activity in the network depends on the spatio-temporal properties of the events to be detected, the latter scenario can be expected to occur more frequently than the former.

5 Experimental Results

We simulated the network for three different values of the threshold. $k = 0$ and $k = 2n$ effectively modeled complete randomized and complete greedy routing. The intermediate value (labeled 'Hybrid') was chosen as $k = \frac{2n}{3}$ for matrix transpose, and $k = \frac{n}{2}$ for row shuffle. Assuming an RTS/CTS packet size of about 8 bytes and typical data packets to be 32 bytes, we used $d = 4$ for simulation purposes.

Figure 2 plots the total latency and total energy consumption of the three routing strategies for matrix transpose, for networks ranging from 100 to 2500 nodes. Figure 4 shows the same for row shuffle. As expected, greedy routing has the worst latency and best total energy for matrix transpose. Also, complete randomization does reduce latency but leads to a large increase in total energy. Hybrid routing with $k = \frac{2n}{3}$ represents an intermediate point with better latency than greedy with slightly more energy consumption. For row shuffle, the important difference is that greedy routing has the best latency as well as the best total energy.

Figures 3 and 5 show the energy balance of the algorithms for a 2500-node network. Lighter regions represent greater energy consumption. Clearly, energy balance of the hybrid and complete random routing strategies is much better than greedy. Simulator details and more analysis appears in [1].

6 Remarks

Threshold randomized routing is a powerful concept that is also very simple to implement. In terms of latency and total energy, we expect TRR (with suitable choice of threshold) to be as good as greedy routing in the average case, while still performing better than greedy approaches in worst-case scenarios as discussed in this paper.

Acknowledgments

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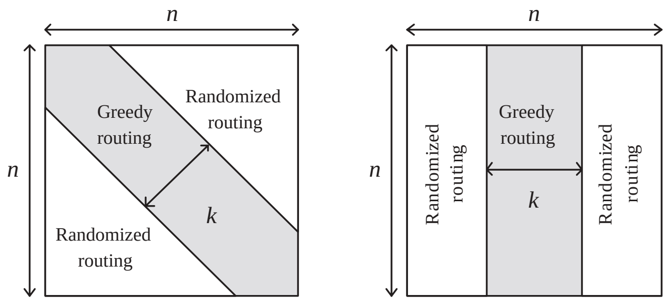

Figure 1. Threshold Randomized Routing: (a) Matrix Transpose, (b) Row Shuffle

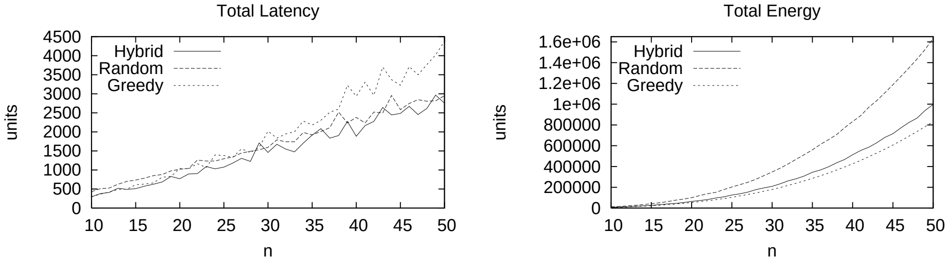

Figure 2. Matrix Transpose: Total energy consumption and total latency

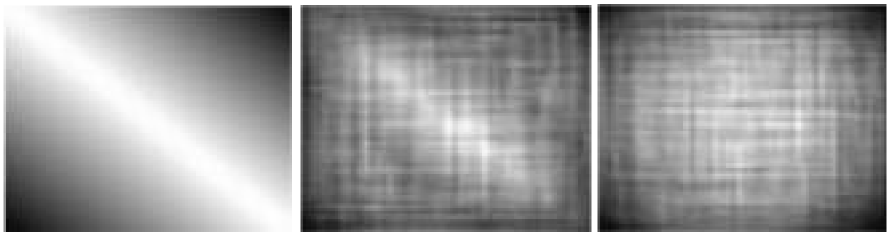

Figure 3. Energy Balance for Matrix Transpose. (a) Greedy, (b) Hybrid, (c) Random

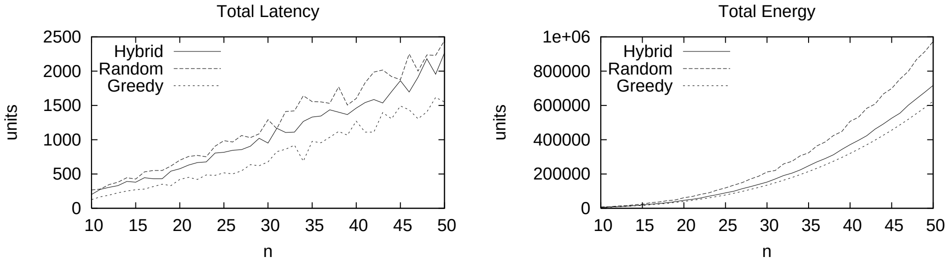

Figure 4. Row Shuffle: Total energy consumption and total latency

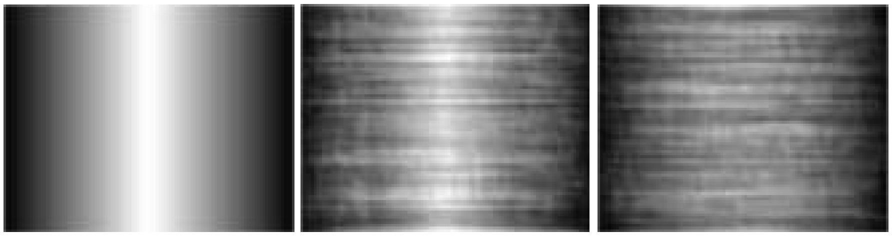

Figure 5. Energy Balance for Row Shuffle. (a) Greedy, (b) Hybrid, (c) Random