Power-Adaptive Routing Topology for Remote Sensor Networks

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Abstract

Remote sensor networks are used everywhere, including civilian as well as military applications. Limited life span is one of the major challenges in designing such networks. The available power in each node is continuously reduced after its deployment irrespective of whether the node is idle or it is communicating with another node. This paper proposes a power-adaptive routing topology to increase the life span of the remote sensor networks. Our routing technique dynamically adapts to the changes in individual node's power levels. This topology uses a decentralized approach on an ad-hoc network. To demonstrate the effectiveness of this approach we simulated multiple networks and compared the life span of these networks using the power-adaptive topology and a least hop topology. The results show that the lifespan of the networks can be improved up to 60% by using our power-adaptive topology.

1 Introduction

In recent years the number of applications utilizing remote sensor networks has been increasing at a staggering rate. Remote sensor networks are being found in commercial, military, and environmental monitoring applications. Such networks are primarily used in hostile environments. While each type of application has different operating requirements, every remote sensor network has the same critical limitations including computation and transmission capabilities, and limited power. This paper addresses the limited power problem by developing a power-adaptive routing technique.

In this paper we will be considering a large ad-hoc network of sensor nodes. We will assume that the nodes are randomly distributed and that their position in the network is static. Each node will have the capability to monitor one or more factors about its surrounding environment and transmit that information to a base-node (sometimes called a "gateway node"). In the situation where an event is detected by a node, the node creates a message describing that event and then transmits back to the base-node. When the base-node is not in transmission range of a sending node, the network must have the capability to route a message from the sending node to the base-node. A specific example of this type of network would be fire detecting nodes spread through-out a large national forest. These nodes would generate a warning message when possible fire conditions were detected. This message must then be routed to the ranger station so that the situation can be handled.

The routing of messages causes a large energy burden on each node along a routing path, as each node must receive this packet and retransmit it while simultaneously powering its own information gathering activities. As a whole the lifespan of the sensor network will be greatly reduced because of the additional drain that routing causes. An even more critical situation is the case when a small subset of nodes is routinely used in the routing path. These nodes experience a drastically shorter lifespan due to the enormous burden of packet routing. When this subset of nodes fails it can even cause "black-outs" in that section of the network. These "black-outs" can not only lead to further routing problems between nodes but also is an area in the terrain that is no longer being monitored by the sensors. In our example of fire detection this is an unacceptable loss.

In the course of routing a packet from a node that generated the packet to a base-node it is common that many possible paths are available to the packet. At each node along the path a decision must be reached by the node to determine which path the packet should follow. Many factors can be involved in these decisions. This paper develops a novel algorithm that allows nodes to route the packets along a path that has the best effect on the overall condition of the network. In other words this routing strategy will increase the lifespan of the network.

The rest of the paper is organized as follows. Section 2 presents related work addressing routing techniques in remote sensor networks. Section 3 presents our power-adaptive routing technique followed by a case study in Section 4. Finally, Section 5 concludes the paper.

2 Related Work

Much research has previously been done in the area of network routing. In the area of power-aware routing most of the current research focuses on the data being routed [1] [2] [3] [4] [5] [6]. This research strives to create nodes that are application aware and can more effectively route data based on decisions made from the type of data the node has generated. As a result of the "named data" certain parts of the network can shut down when they are not needed for that time period. While this approach can be very effective, it assumes complex data types and much knowledge about the current dispersion of the network nodes. These techniques do little for the networks that consist of a few primitive data types and are completely ad-hoc (with no knowledge of the current placements of other nodes).

Currently most routing schemes operate under a shortest path principle [9], [10]. Nodes in this scheme will make the routing decisions based on factors like the shortest number of hops to the base-node or least-cost path in terms of energy needs to transmit at each node. For some networks these schemes meet the operational requirements. However, many networks must operate under the condition that one node failure is not acceptable (such as our previously mentioned example). Consider a situation where a subset of nodes is used frequently to communicate to the base-node, using either of the above mentioned schemes. Even though this path may be the shortest path, it will still fail when that section of the network experiences an overwhelming increase in activity. At first it might have been advantageous to use this path, but after a period of use the path is unable to shift to allow the nodes to use a path with larger power reserves.

Research has been done in the area of path routing to conserve energy and lengthen network lifetime. Sankar et al. [7] and Chang et al.[8] directly address this problem. However, in both cases the solution is derived based on a linear programming solution. This inherently has two problems, the first being that it requires a centralized scheme with great foreknowledge about the network including its node dispersal and frequency at which a particular node will generate a message and send it to the base-node. The second problem is that once it establishes the paths they must be centrally controlled. This greatly hinders the networks ability to adapt to the current node activity pattern.

In this paper we will develop a decentralized routing scheme that will allow dynamic paths. This scheme will allow the network to adapt to the current status of the nodes. We will assume that we have one base-node and no knowledge of the present state of the network after its deployment.

3 P2P Assisted Voice Communication

The central idea of this method is that routing paths through-out the network can change as power reserves in individual nodes diminish. This allows the network routing paths to adjust to activity levels in the network at run-time. To accomplish this goal, each node along a routing path must have the capability to receive and transmit a packet. Each node must also be capable of removing the packet header and attaching a new header to the message. The header will contain information necessary for the routing algorithm. Figure 1 shows the packet structure.

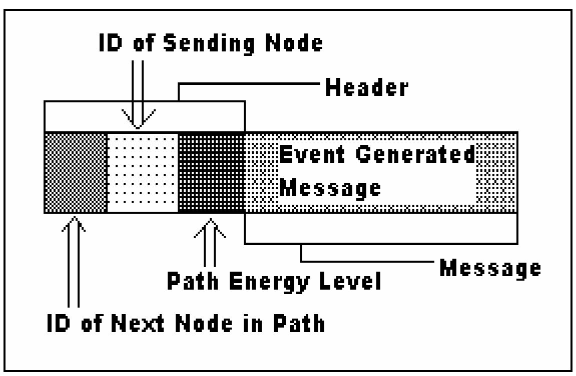

Figure 1: Packet structure

Figure 2 describes our routing algorithm. Once the nodes have been distributed in the field, the network must be initialized. At the time of deployment a nodes neighbors are not known and so must be dynamically configured after deployment. The initialization phase is therefore a necessary step to allow the nodes to determine their “neighbor nodes” and to create the initial routing paths. A “neighbor node” is defined to be all nodes within transmission range of the specified node.

// Nodes are scattered within the target area

1. Initialize the network

2. Event causes a node to generate a message

3. Header is pre-pended to the message to form the packet

4. The packet is transmitted to all nodes in range

5. a) If the receiving node is on the routing path, then
   prepend the new header to the message and transmit

   b) If the receiving node is not on the routing path, then read
   the incoming header and update the routing path of this node

6. Repeat step 5 until the message reaches the base-node

Figure 2: Proposed routing algorithm

3.1 Network Setup and Initialization

To initialize the network we will make use of the header shown in Figure 1 and the path updating process described in Section 3.3. The initialization starts with the base-node sending a mesh type broadcast. A mesh broadcast will transmit the initialization packet to every node in the network. During the initialization phase the network will not follow the power aware routing topology. During this phase the network will facilitate the mesh broadcast topology. However, to properly initialize the network the nodes must continue to attach the packet header with each node transmission. The nodes must also continue to update their routing paths based on the header of the received packet, as discussed in Section 3.3.

Once the initialization phase is complete, each node will have a routing path back to the base-node. The network will then continue to adjust the routing paths as packets are routed through the network, as described in Sections 3.2 and 3.3.

3.2 Message Generation and Routing

As with any network that has directed paths, we must assume that each node has a unique ID that will allow a node to uniquely identify another node. When an event at a node occurs, a message is generated that needs to be relayed back to the base-node. The message is then packaged with the header and transmitted by the node. This transmission is received by nodes within the transmission range. This step is illustrated in Figure 3.

Upon receiving a message, the node then has two options, demonstrated in Figure 6. If the node is part of the path from the message generating node to the base-node (as described in Section 3.1) then the node will receive the packet. The node is the next hop in the routing path if its unique ID number is indicated in the header of the received packet as shown in Figure 1. The node will then strip the header from the packet and add its own header, finally retransmitting the new packet to the next node in the path to the base node. The new header will contain the ID number of the next node in the routing path (Figure 1). If a receiving node is not part of the routing path, meaning that its ID number is not indicated in the header, than it will ignore the message but will use the header in the packet to determine if the sending node has a better path (in terms of network lifespan) to the base-node. If the sending node does have a better path to the base-node then the receiving node will change its routing path accordingly, as described in Section 3.3. This process is illustrated in Figure 4.

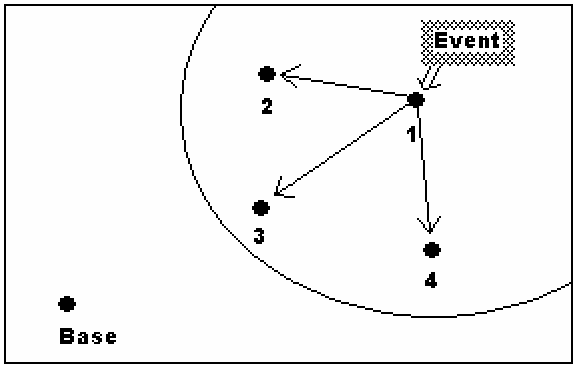

Figure 3: Packet is sent to all nodes in range

To create a topology that routes the packets through the best path in the network we must first determine what defines a “best path”. For our purposes the best path is defined as the path that increases the lifespan of the network. Therefore, our “best path” will be determined by choosing a path that has the largest amount of power remaining in its nodes.

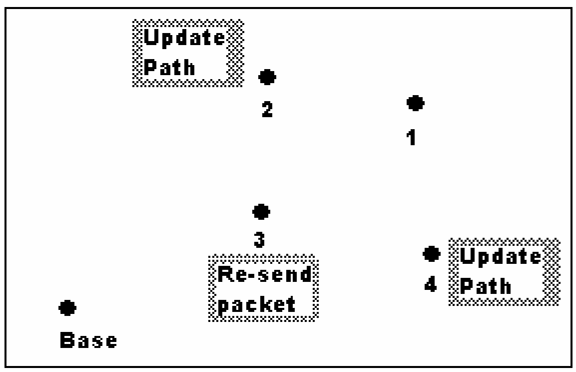

Figure 4: Node either updates path or re-sends packet

This process of receiving the packet and retransmitting it will continue until the packet reaches the base-node. This final step is shown in Figure 5. The routing topology will allow nodes that receive the packets, but are not a part of the routing path, to update their routing paths synchronously with the message routing. Consequently, only a small amount of additional power is needed to allow the routing paths to reconfigure. This process ensures that the network will automatically reconfigure itself to the “best” configuration.

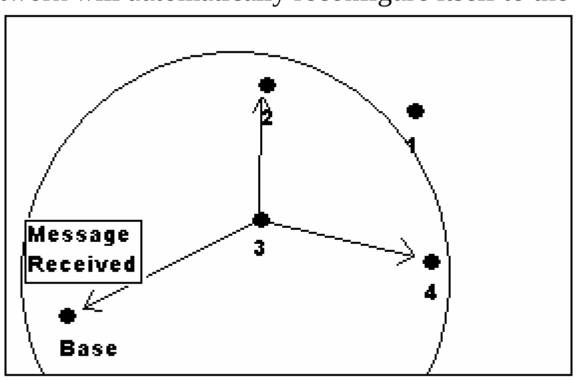

Figure 5: Message is routed to base-node

3.3 Updating Routing Path

During the process of routing a message from an event triggered node to the base-node many non-path nodes will receive the packet being routed. As previously mentioned, these nodes will ignore the message but will examine the packet header. The header will be used to determine if a better path exist than the node's current path to the base-node. Figure 6 demonstrates the algorithm run by each receiving node as the packet is routed to the base node.

Each node, in Figure 6, will compare its current path energy level with the path energy level of the transmitting node. If the receiving node's current routing path has a lower path energy level than the path energy level in the transmitting node, than the receiving node concludes that the transmitting node has a "better" path to the base-node. Consequently, the receiving node will alter its routing path so that it will route its packets to the transmitting node, and updates its new path energy level.

```
ReceiveMessage( NetworkPacket packet ) {
 if (receiving-node.ID == packet.IDNextNodeOnPath) {
   NetworkPacket  newPacket = attachNewHeader( packet.message );
   transmit( newPacket );
 }
 else {
   if ( receiving-node.pathEnergyLevel < packet.pathEnergyLevel )
     setNewRoutingPath( packet.SendingNode, packet.pathEnergyLevel);
   }
}
```

Figure 6: Receiving node routing algorithm

A path energy level can be defined as a measurement of a specific routing path taking into account factors which can directly affect the paths ability to be sustained. We use the path energy level concept in order to measure a routing path using only one variable. For the purposes of this paper we used residual energy in each node along the routing path. The path energy level is therefore equal to the remaining energy in the node with the lowest power level along the routing path.

An additional consideration is that the base-node must be assigned a path energy level value that is logically equivalent to infinity. This will cause the desired effect that if any node is in range to transmit to the base-node it will always route directly to the base-node.

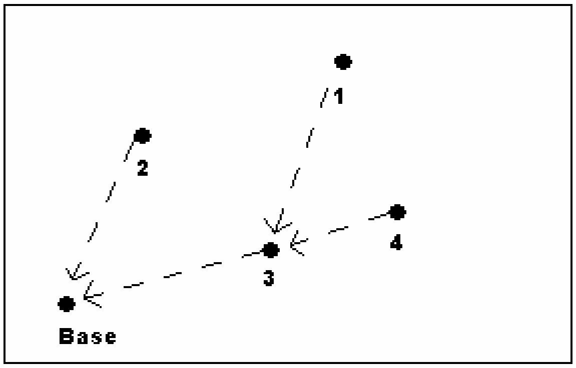

Figure 7: Initial routing paths

Figure 7, demonstrates a network routing scheme where nodes 1 and 4 will both route their packets to node 3 which in turn will route the packet to the base-node. If we assume node 3's power level falls below node 2's power level due to a large frequency of events in node 4, then the next time node 2 sends a packet, node 1 will update its routing path, as shown in Figure 8 (using the algorithm in Figure 6).

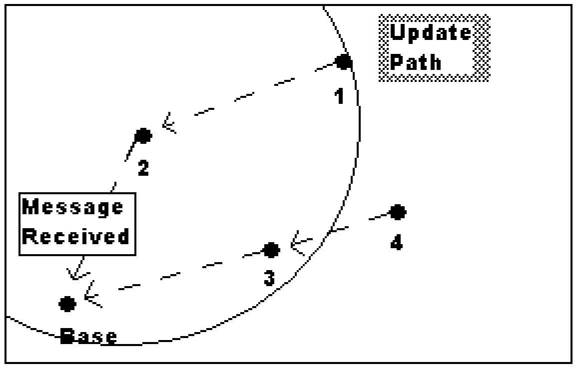

Figure 8: Updated routing paths

4 Experiments

To determine if our new adaptive routing topology would increase the lifespan of a remote sensor network we compared it against a least-hop routing topology. Of the topologies available this scheme is the most efficient given our constraint that the topology must have no central control and assume a completely ad-hoc network.

4.1 Experiment Setup

We have developed a sensor network simulator. The simulator creates a remote sensor network by randomly placing nodes inside a specified dimension and gives the nodes a randomly determined residual power supply. The emulator will then use this specific node configuration to create a least-hop topology network and a power aware network topology. Identical sensor activity is then simulated concurrently on the two networks. As mentioned earlier one node failure is treated as a network failure.

For each node configuration pattern, multiple different random node activity patterns are run. The emulator assumes one base-node and a fixed node transmission radius. In the case of a tie between two path energy levels a node will use a least-hop algorithm to determine the "best" path. Thus, it is possible for the network routing paths between the two networks to be similar at times.

To avoid loops being formed between two or more nodes a Boolean value was included in the packet header. This value was set to true if the sending node had path that lead back to the base-node and false otherwise. If a node attempted to update its path using a received packet header it would only change its routing path if the boolean value was set to true. Thus, a new path could only be formed if it routed to the base-node.

4.2 Non-centrally placed vs. centrally placed base-node

We wanted to test the effects of this topology on a sensor network with a non-centrally placed base-node. Therefore, for this test the base node was placed in the corner of the network, only allowing nodes to be placed in the 90^0 arc in front of the base node. Additionally, the network dispersal parameters were set so that the area covered by the sensor nodes was approximately 40 times larger than the transmission radius of each individual node. Figure 9 shows the results of this test.

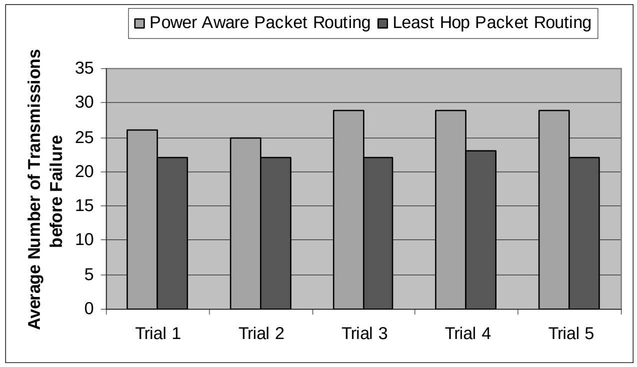

Figure 9: Large network, base-node placed in corner

In Figure 9, each trial represents a different random node dispersal within the given parameters. Each trial was run 100 times with a different node activity each time. The number of messages generated and routed back to the base-node was then calculated for each routing topology. The numbers in the graph represent the average of the 100 runs of each trial. Observe that in all five trials the power aware routing topology survived the longest before having a single node failure.

The next test was to determine if similar results were reached when placing the base node in the center of the sensor network, while keeping everything else constant. For this test the network parameters were again set to create a network much larger than the transmission radius of a single node. However, this time the base-node was placed in the center of the network. This placement of the base node allowed sensors to be placed 360^0 around the base node. The results from this test are seen in Figure 10.

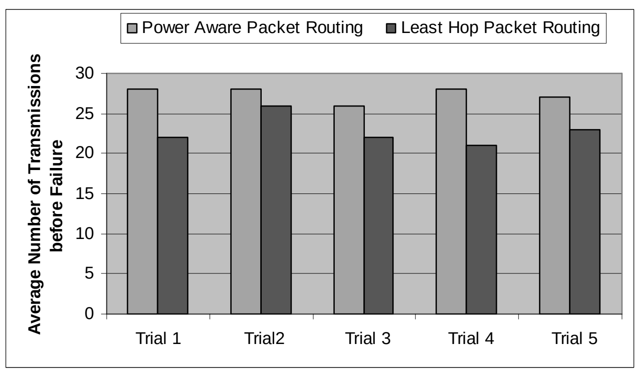

Figure 10: Large network, base-node placed in center

From this test we can see that the results are similar to the first test, the power aware topology produced a longer lifespan than the least hop routing topology. When we compare these two tests we see two cases, the first case (base-node in the corner) creates a situation where there is only a few nodes that can transmit to the base-node. In this case we force a scenario where we have a small subset of nodes that every packet must be routed through. The second case (base-node in the center), demonstrates a node placement pattern that has a larger number of nodes that can transmit to the base-node. These two tests allow us to compare the performance of the two topologies when considering if a network has a sub-set of nodes that must be routed through. When we take into account the data from Figure 9 and Figure 10 we can conclude that the power aware topology out performs the least-hop topology irrespective of the placement of the base-node.

4.3 Large network vs. small network

For this phase of testing we assumed a base-node placed in the corner. In Figure 9, we show the test results when comparing the power aware topology and the least hop topology while using a large network.

As mentioned in Section 4.2, this test used a base-node placed in the corner of the network and network parameters set so that the area covered by the sensor nodes was approximately 40 times larger than the transmission radius of an individual node.

To compare these two topologies under the conditions of a small network we created a network that covered an area approximately 17 times larger than a nodes transmission radius. As per our assumptions for this phase of testing, the base node was placed in the corner of the network. The results for this test are shown in Figure 11.

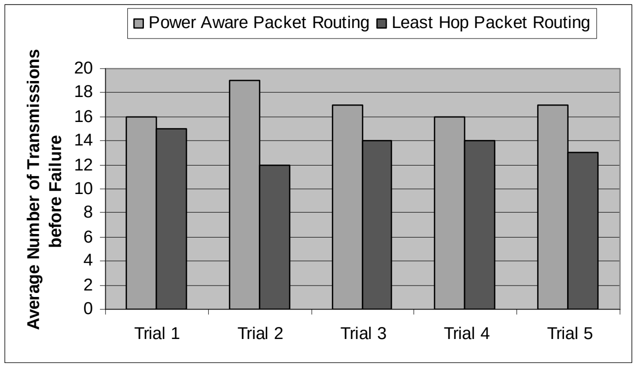

Figure 11: Small network, base-node placed in corner

The results depicted in Figure 9 and Figure 11 shows that the power aware routing topology will create a longer network lifespan regardless of the network size.

4.4 Increase in network lifespan

Through all three configurations (Figure 9, Figure 10, and Figure 11) an average of 80% of the tests produced the same results between the two topologies (least-hop and power-adaptive). However, none of the test showed the least hop topology to produce better results than our power-adaptive topology. The remaining 20% of the tests showed that our power-aware topology produced up to 60% longer lifespan in the network. The increase in network lifespan is shown in Figure 12.

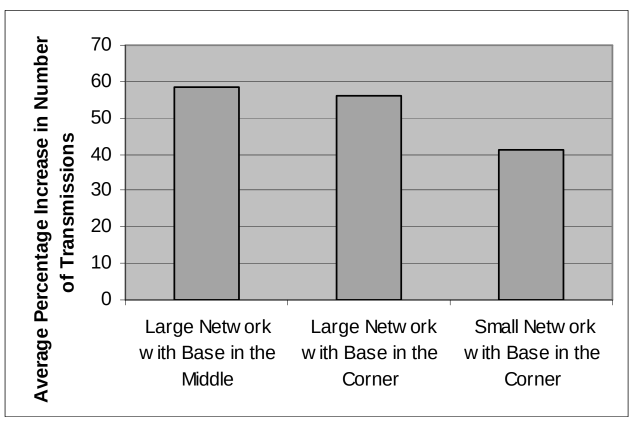

Figure 12: Percentage increase in networks using power-aware routing topology

In Figure 12 we can see that the number of transmissions that the power aware topology allowed before a node failure was a large increase over the least-hop topology.

5 Conclusion

Remote sensor networks are increasingly being found in a wide variety of applications. While each type of application has different operating requirements, every remote sensor network faces the limited power problem. This paper presented a power-adaptive routing topology to address this problem.

Our technique dynamically changes the routing paths based on the available power in the sensor nodes. We have compared our method with a least-hop routing technique to demonstrate the usefulness of out approach. The experimental results showed that our power-adaptive routing topology produced increased life span over least-hop routing topology irrespective of the network size and the placement of the base node. Our approach to a power-adaptive topology requires very little computational overhead and no additional transmissions. Our technique does not require additional hardware and can be easily adapted to existing networks. Our future work includes implementation of our algorithm on a deployed remote sensor network.

6 References

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