A Distributed Coverage-Preserving Multipath Routing Protocol in Wireless Sensor Networks

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***Abstract* –** A major challenge in sensor network is to preserve the coverage of the sensing network for the maximum possible time. This is done by putting redundant nodes to sleep [1] [11] when the density of nodes is high. When the density is sparse, coverage needs to be preserved by using energy-efficient route-selection algorithms. Several routing algorithms have been proposed that conserve energy while increasing the lifetime of routes. However, they do not address the problem of preserving network coverage. In this study, we investigate two algorithms -- 1) Min-max Active Node Routing algorithm (MANR) and 2) Min-max Active Node Routing algorithm with Max-min energy extension (MANR-Max) -- which attempt to preserve network coverage. We also propose a metric (Standard Deviation of Source Partition times) to measure coverage. We show that our proposals perform better than previously-proposed algorithms, namely Minimum Total Transmission Power Routing (MTTPR) and Min-max Battery Capacity Routing (MMBCR) [8] in terms of network coverage and first-source partition time without compromising on other performance metrics.

Keywords: sensor networks, ad hoc, multipath routing, coverage, energy

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I. INTRODUCTION

Wireless sensor networks consist of small and cheap nodes, which have limited power, limited computational ability, and short communication range. Since the scenarios where these networks are used include remote locations, the nodes are often inaccessible, and they are often deployed in an *ad-hoc* manner, i.e., there is typically no fixed infrastructure for sensor networks.

Routing in wireless sensor networks is different from routing in conventional networks due to these limitations. Since communication between nodes occurs over wireless channels and depends on the *transmission range* of the nodes, intermediate nodes assist in forwarding packets towards the desired destination node.

Thus, *energy-efficient routing* is very important in wireless sensor networks. There is loss of network coverage when a source can no longer send data packets to the base station because all the available routes have failed (where base station is a designated node to which all nodes need to communicate their data). The time when such partitioning occurs is called *source partition time*. Complete loss of coverage occurs when all the sources have been partitioned.

It should be noted that network coverage could be affected even while keeping the network lifetime constant. This happens when source nodes with more routes to the base station continue to use the routes which they share with other source nodes with fewer routes to the base station. This way, network partition will occur sooner but the total network lifetime will still be the same because the lifetime of the first source node is extended at the expense of the other nodes.

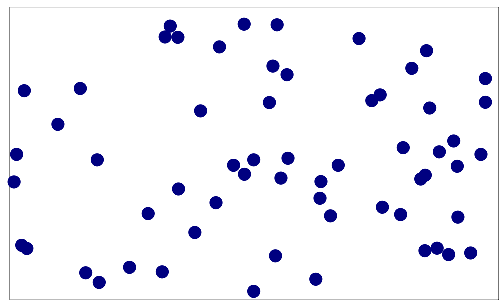

Fig. 1. Random deployment of 60 nodes in a 200m by 200m region

Multiple paths between a source node and a base station could be used to distribute the traffic load. Multipath routing is useful and relevant in sensor networks because the typical mode of communication in a sensor network is from multiple data sources to a single base station (which is typically a "data logger" and which typically communicates with the fixed network infrastructure). The nodes and the base station communicate with each other using packets. Furthermore, in most scenarios in which sensor networks are used in, the sensors are not mobile. It is easier to maintain multiple routes between source nodes and a single base station rather than between every source node and all other nodes. Moreover since the nodes are not mobile, the energy-expensive route-discovery process needs to be done only once.

By using energy-aware routing [9] [13], a balance between draining the same (shorter) path all the time and using other more expensive paths can be achieved. This strategy ensures that there is more uniform dissipation of energy among the nodes on all the paths. This approach also helps in increasing the *resilience* of a sensor network. Multipath routing also helps in preserving coverage because in unipath routing, when the route breaks down, the source node is partitioned from the rest of the network till the route-discovery process takes place once again.

We review existing multipath routing protocols and algorithms in ad hoc networks in the next section. Then, we describe our approaches in Section III, and evaluate them and compare them with previous approaches in Section IV.

II. BACKGROUND

A major design goal in sensor networks is to maximize the network lifetime. In addition, the maintenance of total coverage for the maximum possible time is also a major design issue. When the node density is high, the redundant nodes (for purposes of store-and-forward traffic routing) follow a scheduling scheme [1] [11] by which they sleep and wake up alternately to save energy. Some of the multipath routing protocols that have been proposed in ad hoc networks are Split Multipath Routing (SMR) [10], Ad hoc On-demand Distance Vector – Multipath (AODVM) routing [14], Ad hoc On-demand Multipath Distance Vector (AOMDV) routing [5], and Multi-Path Dynamic Source Routing (MP-DSR) [7]. MP-DSR and SMR are extensions to DSR [3] and are used to construct multiple paths. SMR is used to construct two maximally-disjoint paths, which means that the routes have as few common links as possible. MP-DSR attempts to provide end-to-end reliability by providing multiple paths that fulfill a certain path-reliability requirement. AOMDV and AODVM are extensions to Ad hoc On-demand Distance Vector (AODV) routing protocol [6] for computing multiple loop-free, link-disjoint and node-disjoint paths.

After a source node discovers multiple paths to the destination node, it has to choose which route to use depending upon the performance metric considered by the routing protocol. The route-selection protocols that have proposed so far try to extend the failure of the first node. A comparison of several energy-aware route-selection protocols in mobile ad hoc networks is conducted in [3]. Various routing protocols such as Minimum Total Transmission Power Routing (MTTPR), Min-Max Battery Cost Routing (MMBCR), and Conditional Max-Min Battery Capacity Routing (CMMBCR) [12] are analyzed. The algorithms mentioned depend on centralized information, and they attempt to maximize the time to failure of the route. Energy information of all the nodes in the network is expensive to obtain as it keeps changing dynamically and signaling this information may cause quite a lot of network overhead.

MTTPR always picks the route that uses the minimum energy to send or receive information. The disadvantage of this protocol is that, even though the total energy of the network remains maximum, it does not consider some of the metrics mentioned above, thereby resulting in network partitions, route failures, and disparities in the energy depletion of different nodes. In MMBCR, the cost is the reluctance of a node to forward a packet and is inversely proportional to the battery capacity of the node. The algorithm examines all the routes present and selects the route that has the maximum capacity. This approach ensures that all the routes from a node to a destination will remain available simultaneously as long as possible and will have similar lifetimes. The disadvantage of this approach is that even routes, which consume a lot of energy, may be selected for routing, thus reducing the total energy of the network.

CMMBCR [12] takes into account both the *battery capacity* of the nodes as well as the total energy consumed by the route, while selecting a path for routing.

The above-mentioned route-selection algorithms do not consider other important factors such as network coverage and network partitioning as well. Hence, we propose a distributed multipath routing protocol that considers network coverage as the quality-of-service (QoS) metric, and compare its performance with those of the MTTPR and MMBCR routing algorithms.

III. OUR PROPOSED APPROACHES

Network lifetime, as we have defined, is similar when MTTPR, MMBCR, or our algorithms are considered, with node-disjoint paths and when overhearing costs are ignored. Even while considering node-disjoint paths, when there is more than one source sending data packets to the base station, there exists the possibility that a node could be used in multiple sources' paths for routing. Therefore, the lifetime of the network depends on the following factors:

1. Number of sources, n.
2. Number of routes for each source, m.
3. The number of routes, the most active node in each route is participating in, c.
4. Initial energy of the nodes (constant), E_i.
5. Energy used for receiving and transmitting a single packet (constant), E_j.

Thus, when all the routes from a source are node disjoint, we can write:

$$\text{Network lifetime} = \sum_{i=1}^{n} \sum_{j=1}^{m} E_i / (E_j * c)$$

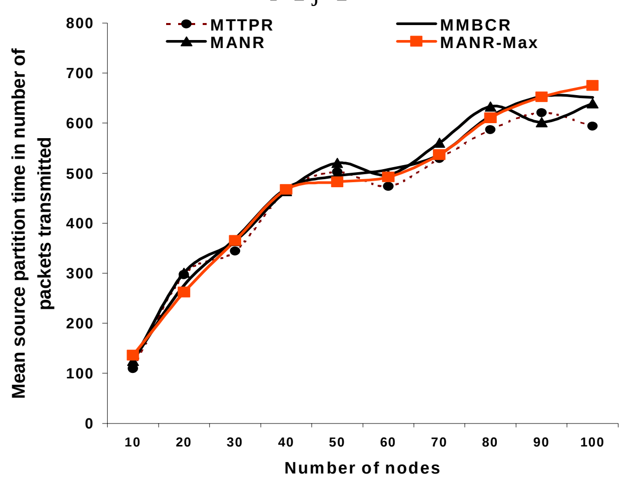

Fig. 2. Mean source-partition times of different algorithms in terms of total packets transmitted.

Since the above-mentioned factors remain the same for all node-disjoint multipath routing protocol, the network lifetime is the same for all the protocols. This is shown in Fig. 2 where all the protocols show similar network lifetimes for all sets of nodes considered. (Details of the simulation models used to obtain these results will be stated later in Section IV on experimental results.) Therefore network lifetime is not an appropriate performance metric to compare routing algorithms. Like network lifetime, first-node failure is not a good performance metric either if the failed node is not a source node, or if the source node using the failed node for routing has other routes to fall back on as alternate paths.

In our routing protocol, when a source needs to send data to the base station, it broadcasts a Route Request (RREQ) if it does not have any existing route. When an intermediate node receives an RREQ, it checks the packet to see if it has already received this RREQ before. If it is receiving this RREQ for the first time, the node will update its routing table with the source address of the RREQ and the node it received the RREQ from. It also adds its own address to the RREQ and re-broadcasts it. When the base station receives more than one RREQ, it replies back along only the node-disjoint ones by sending a Route Reply (RREP) message. All the intermediate nodes check and update the *activity* field in the RREP.

The *activity* field contains the maximum number of flows through any node in the route. When a source node receives an RREP, it will know the number of routes, and the most active node in each route. The source node makes its route-selection decisions based on the *activity* field in the RREP. As other source nodes start sending data to the base station, the *activity* of the participating nodes might change. These participating nodes inform the source nodes about this change through updates and *activity* of the route is updated accordingly.

Singh et al. [8] have proposed power-aware metrics to measure the performance of a routing protocol in a mobile wireless ad hoc network. These metrics describe the goals for selection of routes and conserving energy in that particular manner. In addition to the proposed metrics, variance in source partition times and time to first-source partition are important metrics to be considered.

So, we propose a route-selection algorithm, which takes *time to source partition* as a performance metric. Both MMBCR and MTTPR consider only first-node failures, but they do not consider *source partition* time, network lifetime, and network coverage. When a source node fails or when source partition takes place, there is loss of network coverage. One parameter to measure network coverage is the variance of all source partition times. The lower the variance, the better is the network coverage. Our algorithm performs well in terms of both network lifetime and network coverage.

We take the number of routes, and the most active node in a route as the selection criteria for our algorithm. We use the route that has the *min-max active routing node* in it. We call our algorithm *Min-max Active Node Routing* (MANR) algorithm. This is done so that a source uses a route which least affects the source-partition time of another source when it has other paths to choose from.

MANR Algorithm

FOR all source nodes, i=1 to n, in the network
  FOR all routes, j=1 to m, of a particular source node
    Check if most active node of current route is less active than previous Min-max active node
      If yes,
      Min-max active node = current node,
      and Min-max active node route = current route.
      End FOR
End FOR
Send the data packet from the source to the first node on the Min-max active node route.

However, simulation results in Fig. 2 indicate that the first-node failure time for MANR is much lower than MMBCR even though it is higher than in MTTPR. So, if time of first-node failure is also important while maintaining good coverage, we use the Min-max Active Node Routing algorithm with Max-min energy extension (MANR-Max). In this approach, if more than one route from a source has equally active nodes as max-active routing nodes, then the route with the max-min energy node is chosen for routing. This is done to maximize the time to first-node failure time while maintaining network coverage. Simulation results in Fig. 3 show that the first-node failure time has improved considerably.

The *Min-max active routing node* algorithm ensures that, if a source has more than one route and it shares a routing node with another source which has only one route, then the first node does not use its shared route frequently early on. Otherwise, the source-partition time of the second node would come down because the shared routing node's energy level would decrease faster.

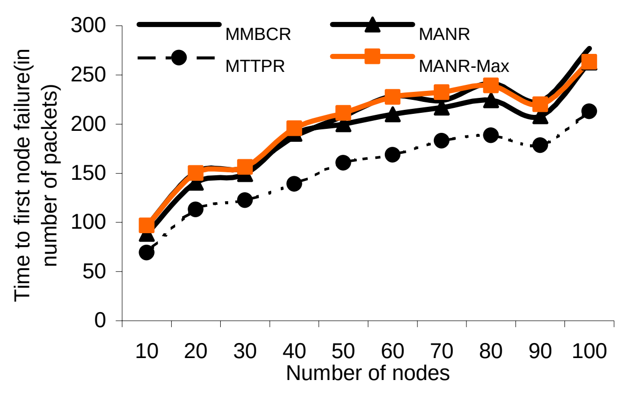

Fig. 3. Time to first-node failure using different algorithms in terms of total packets transmitted.

MANR-Max Algorithm

FOR all source nodes, i=1 to m, in the network

FOR all routes, j=1 to n, of a particular source node
Check if most active node of current route is less active than previous Min-max active node
If yes,
Min-max active node = current most active node, and Min-max active node route = current route
If no, check if the most active node is as active as the previous Min-max active node
If yes, check for the weakest nodes in the two routes.
Make the route, which has the stronger-weaker node among the two, the current Min-max active route.
Make the most active node on that route the Min-max active node.
End IF
End FOR
End FOR
Send the data packet from the source to the first node on the min max active node route.

By avoiding this, we ensure that traffic from all the sources is balanced between the available routes. This would reduce the variance of the source partition times, thus improving the network coverage of the topology. Moreover this algorithm should perform better than the Minimum hop routing algorithm in terms of first node failure.

IV. ILLUSTRATIVE NUMERICAL EXAMPLES

We use the ns-2 simulator [2] to implement coverage-aware routing in wireless sensor networks by extending the AODV routing protocol [6] for wireless ad hoc networks. We consider a rectangular region of area 200m by 200m, in which the wireless sensor nodes are deployed in an ad hoc manner. The nodes are assumed to be static and have the same initial energy of 0.5 Joules (J). There is one base station to which all the sensor nodes in the network need to send their data packets. The transmission power of a node is 0.8 mW. Packet transmissions consume energy depending on the packet-length, and data packets consume more energy than control packets.

A node can receive a data packet from another node only if it is within the transmission range, i.e., 80 meters, of the node. The energy spent while receiving packets has not been considered because it would be the same for all routing protocols since they use the same routes. A node failure occurs when the energy consumed by a node is greater than 0.5 J.

We have so far compared our algorithms with MTTPR and MMBCR in terms of first-node failure and network lifetime. Now, we compare our algorithms in terms of achieved network coverage and first-source partition time. We compare the performance of the algorithms over 80 trials with respect to the following metrics:

a) Standard deviation of source partition times. The lower the standard deviation, the better the network coverage is. This means that traffic from different sources are load balanced among available routes such that well-connected sources do not use routes of less-connected sources which, thus, provides coverage for a longer time.

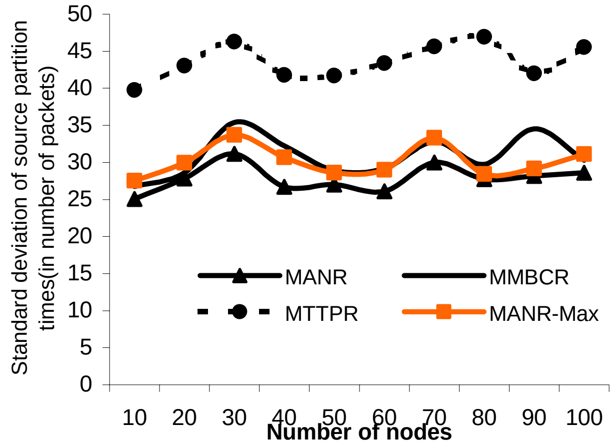

Fig. 4. Standard deviation of source partition times in terms of total packets transmitted.

b) First-source partition time, i.e., the time when the first source fails to find a route to the base station. This is more important than first-node failure because this gives us the first instance of network coverage loss.

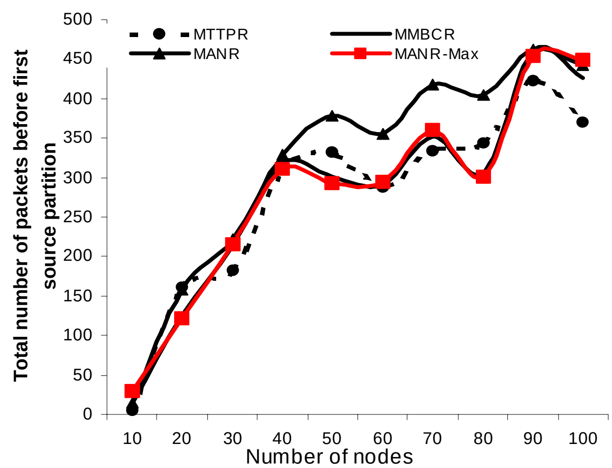

Fig. 5. First source-partition time using different algorithms in terms of packets transmitted.

The simulation results can be seen in Figs. 4 and 5. It can be seen that MANR outperforms all the other three algorithms in both the metrics considered. Our simulations show that MANR performs 11% and 15% better than MMBCR and MTTPR, respectively, in terms of first-source partition times. In terms of standard deviation of source partition times, MANR performs 9% and 35% better than MMBCR and MTTPR, respectively. Even MANR-Max performs slightly better than the other two algorithms in both the metrics considered. This shows that MANR algorithm maintains network coverage for a longer period of time than other algorithms considered.

The overhead for updating the source node about the energy levels of the routing nodes (as needed by MMBCR) has not been considered. If this overhead was also taken into consideration, the difference in performance between MANR and the other algorithms will be even greater.

V. ENHANCEMENTS

Some enhancements, which are going to be considered in the near future, are discussed below. An important enhancement to improve coverage would to combine these coverage-preserving routing algorithms with coverage-preserving node-scheduling algorithms. This will be helpful in maintaining coverage of networks of all node densities over a long period of time.

Placement of redundant nodes in high-traffic areas would preserve coverage for a longer period of time. In the simulations run to obtain Fig. 6, the transmission range is 80 meters. As can be seen, for all the algorithms considered, the distance of first-node failure from the base station is between 60 meters and 75 meters. This means that the nodes, whose distance from the base station is equal to their transmission range, have higher traffic. Such regions need to be identified and redundant nodes should be placed over there.

If the density of nodes is high and a lot of nodes are source nodes, then another enhancement would be to ensure that paths, which contain nodes that have nearby nodes covering the same area or almost the same area, are used more. This would reduce the effect of a node failure if the functions of the node were covered by another node. This would help in maintaining network coverage for a longer period of time.

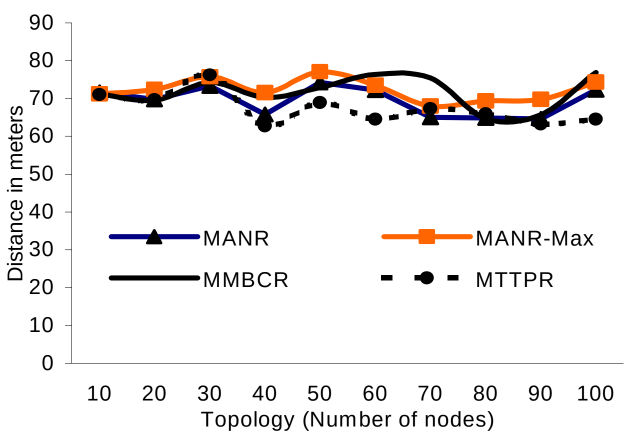

Fig. 6. Distance of first-node failure from the base station, for transmission range = 80 meters.

VI. CONCLUSION

In this study, we investigated the limitations of some existent routing protocols in sensor networks in terms of maintaining network coverage. We also proposed two low-overhead, distributed algorithms -- MANR and MANR-Max -- in which these limitations are reduced without compromising on other performance metrics. MANR and MANR-Max algorithms were compared with the existing algorithms, and results from simulation experiments show that they preserve network coverage for a longer period of time than MTTPR and MMBCR.

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