Zonal Rumor Routing for Wireless Sensor Networks

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Abstract

Routing algorithms for wireless sensor networks are constrained by power, memory and computational resources. Rumor Routing algorithm for sensor networks spreads the information of an event to other nodes in the network, thus enabling queries to discover paths to the events. Zonal Rumor Routing (ZRR) is an extension to the Rumor Routing algorithm. ZRR algorithm enables the rumors to spread to a larger part of the network with high energy efficiency by partitioning the network into zones. New algorithm improves the percentage query delivery and requires fewer transmissions, thus reducing the total energy consumption in a sensor network. Rumor Routing can be considered as a special case of ZRR when only one node belongs to one zone. The performance of ZRR, the effect of zone size, and the scalability of the algorithm are evaluated using simulations.

Keywords
Sensor Network, Routing, Wireless, Rumor Routing

Introduction

Recent advances in sensor networking technologies have allowed sensor networks to be used for numerous applications such as environment and habitat monitoring [2,9]. Such applications generally require a large number of sensors, which are constrained by battery power, memory and computation resources [4,6]. Moreover, sensor networks may be deployed in inhospitable environments, where frequent access to sensors is not possible. Wireless communication links between sensors may also degrade due to environmental interferences. Operational life of sensor nodes is limited by the energy consumed during their operation. Therefore the protocols designed for sensor networks should efficiently use the available resources. Since sensor networks may vary in size, sensor density, and frequency of sensing, protocols deployed in a sensor network should scale well with these factors. In a sensor network, events are detected or monitored by sensor nodes. However these events may be of interest to other nodes not in the vicinity of the node detecting the event. Therefore, information about these events has to be relayed to nodes interested in those events. Moreover, nodes may also generate queries to find events they are interested in. Thus there is a need to route the information about the observed events to other nodes in the network. Different routing algorithms have been developed for sensor networks. Routing algorithms that flood the network with events or queries for reliable delivery [3,7,8] of the event information, require relatively high energy consumption [1]. Some routing algorithms are dependent on the geographical locations of the sensors [10,11]. For sensor networks in which it would be impossible to determine the exact locations of the sensors, such algorithms are unacceptable. There exist routing algorithms that need not be aware of the physical location of the sensor nodes for routing [1,3,7,8].

Gossip routing [8], which provides reliability in network broadcast, is more efficient than the flooding scheme in terms of traffic generated for query delivery. This routing algorithm however was not designed to work in energy constrained sensor networks. However, directed diffusion [7] performs a limited flood towards the event, and then selects the best path for transmitting the data. This algorithm also floods the network with queries.

Rumor Routing algorithm proposed by Braginsky and Estrin [1] achieves significantly higher energy efficiency than the algorithms in [3,7,8]. In this paper, we present an extension to Rumor Routing, Zonal Rumor Routing (ZRR). ZRR algorithm improves the percentage query delivery and generates fewer transmissions, thus reducing the total energy consumption in a sensor network compared to traditional Rumor Routing algorithm. In ZRR, the network is partitioned in to different zones where each sensor node is a member of exactly one zone. The objective of this approach is to spread agents and queries to a large part of the network by moving from zone to zone using long steps. Simulation results presented in the paper show that ZRR can lead to a significant improvement in energy efficiency and query delivery over traditional Rumor Routing algorithm. In case when sensors are uniformly distributed in a sensor field, there exists a zone size for a given network, which gives the highest query delivery rate or requires

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lowest number of transmissions. We also explain how to obtain the zone size at which minimum cost of delivery is achieved for the case when sensors are uniformly distributed in the sensor field. This paper also discusses the scalability of ZRR with respect to sensor density.

Section 2 briefly describes the different terms and the motivation for improvement of Rumor Routing algorithm. Section 3 presents the ZRR algorithm. Section 4 outlines the simulation details, and Section 5 discusses the results. Section 6 concludes the discussion on ZRR.

2. Background

2.1. Definitions

Agents: An agent is a packet that is responsible for spreading rumors about the events in the network. Each agent is associated with the time to live (TTL) that determines the number of hops the agent can traverse before it dies. An agent maintains an event list and a history list for its operation.

***Query*:** A query is a request packet for receiving information on a particular event. Each query is associated with a time to live (TTL) that determines the number of hops the query can make. A query is considered undelivered when it does not reach its destination before the expiration of TTL. Like an agent, a query also maintains a list of visited nodes or zones in a history list.

Event List: This list stores the event names and the distance to the events. Agents and nodes maintain their respective event lists.

Neighbor List: In case of Rumor Routing, neighbor list stores the node ids of the neighbors. In case of ZRR, neighbor list stores the node ids and the zone ids of the neighboring nodes.

History List: In case of Rumor Routing, history list stores the node ids of the previously visited nodes. In case of ZRR, history list stores the zone IDs of the previously visited zones.

If any of the event list, neighbor list or history list overflows, then FIFO mechanism is used to replace the old entries in the lists. These lists maintain soft state information.

***Communication Range**:* Communication range is the maximum distance that a node can send packets to through wireless transmission. Therefore each node can send packets to other nodes that are within its communication range. In this paper, a circular propagation model is assumed for the wireless communication, although this is not a necessary condition for ZRR.

Sensing Range: This is the maximum range of each sensor node in which a sensor can detect the events. A sensor can detect multiple events occurring within its sensing range.

Event path: Along with spreading the rumor, the agent also constructs the event path, which is the shortest distance to the event the agent has discovered yet.

2.2. Need for zones in Rumor Routing algorithm

In Rumor Routing [1], next hop for agent transmission is randomly selected. The neighboring nodes that are near to the agent node will have equal probability of being selected as the distant neighboring nodes that are within its communication range. Selection of distant nodes within the communication range provides an opportunity to move farther from the agent node, thus allowing the agent to spread rumor to a larger part of the network. Selection of nearby neighboring nodes may lead to redundant transmissions, and rumor may remain concentrated in a small region of the network. This limitation may be overcome by partitioning the network into zones as illustrated in the next section.

3. Zonal Rumor Routing (ZRR)

In Zonal Rumor Routing, the network is partitioned into zones, where each node is a member of exactly one zone. Zones are partitions of the network such that any node present in that area becomes a member of that zone. Each member node of a zone stores the zone id of that zone. In Rumor Routing, the agent or the query randomly selects an unvisited neighboring node as the next hop. In ZRR, the agent or query randomly selects a neighbor in an unvisited neighboring zone. Simulation results presented below show that decision for next hop in ZRR significantly improves the query delivery rate and transmission costs of query delivery as compared to the Rumor Routing algorithm.

3.1. Algorithm overview

The network consists of wireless nodes, each with a certain communication range. The nodes can sense events within their sensing range. Every node maintains a list of its neighbors and their respective zones. Every node also maintains a list of events that the node has either observed or learned about through the agents. Each node's event list also records the distance to each event source. Three steps are involved in the ZRR algorithm.

3.1.1. Zone creation: There are different ways in which zones can be created, e.g., using the k-clustering approach [5] or even pre-configuration. In this paper we use the following scheme for zone creation.

Each node is assigned a probability of being selected as a zone leader. When the node starts up, it probabilistically becomes the leader of a unique zone. Zone leader broadcasts zone creation announcement message asking any other node to join the zone. If the node that receives the broadcast is already a member of any other zone, it broadcasts back the information containing its unique node id and zone id. Zone leader updates its neighbor list with the received node id and zone id on hearing the return broadcast. All other neighbors ignore this return broadcast. In the other case, if the node that receives the leader's broadcast has not joined any zone, it joins that zone. The new member node then forwards the zone creation announcement further asking its own neighboring nodes to join the zone and updates its neighbor list on hearing return broadcast. The zone leader that had sent the initial broadcast receives this forward broadcast (as zone leader is one of the neighbors) and updates its neighbor list with their zone ids. The zone creation messages are propagated through the network until all nodes stop receiving any announcement messages. After some time, the network stabilizes which means that each node has become a member of exactly one zone. For a constant number of sensor nodes in a network, higher the number of zones lower is the average zone size in a given network. Average zone size denotes the average number of nodes in a zone. Once the network has been partitioned into zones, the nodes are only aware of their own and neighboring nodes zone membership.

3.1.2. Agent routing: After the zones have been created, the algorithm runs quite similar to the traditional Rumor Routing algorithm. When a node detects an event, it probabilistically generates an agent. The node records the event and sets its distance to the event as zero. The agent creates an event list for storing event information; it also creates an empty history list of visited zones. The agent then adds the zone of the node that created the agent to its history list. In order to determine the next hop, agent selects a neighbor, which is in a zone different from the zones in the history list. Once the agent finds a neighboring node that is in a different zone, the agent is forwarded to that node using broadcast as shown in figure 1. When the agent arrives at the destination node, it synchronizes its event table with that node. All the neighboring nodes that receive this broadcast synchronize their event list with the agents. It is important to note that only destination node modifies the event list of the agent. Other neighboring nodes do not modify the event list of the agent, but modify their own event lists only. The agent can be forwarded to the next hop by the destination node in a similar manner. At every node, the agent selects a node for its next hop if it is in a zone different from the zones in the history list. If the agent fails to find any node that is in a different zone, then it randomly selects a neighboring node similar to Rumor Routing algorithm.

3.1.3. Query routing: Any node may generate a query interested in a specific event. The query traverses through the network similar to an agent. Query searches event list at each intermediate node, if node has a route to the event, it forwards the query in that direction. Figure 1 shows a possible path taken by a query. If a route does not exist, then the query selects a neighbor that is in a different zone than the query's zone. If it cannot find a different zone, then the query selects a random neighbor for its next hop.

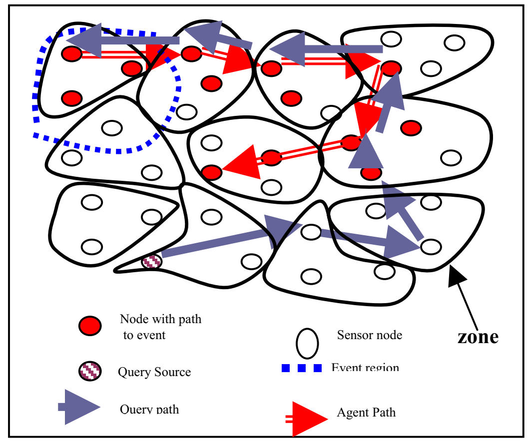


Figure 1: Agent and Query traversal in ZRR algorithm

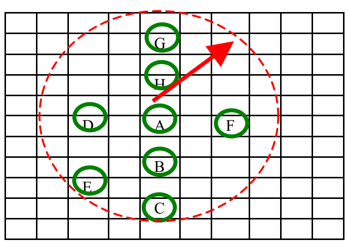
3.2. Optimal number of zones

The objective of the ZRR algorithm is to spread the rumor of the event as far as possible in the network with minimum number of transmissions in order to increase the query delivery rate. Therefore goal of the agent is to choose the next node that gives the longest leap to the agent. The expected behavior of the agent can be illustrated by the Figure 2. It is assumed that sensors are uniformly distributed in the sensor field. A, B, C, D, E, F, G and H are sensor nodes in the network. The dotted circle represents the communication range of node A. Therefore all nodes inside the dotted circle are considered adjacent neighbors of a node A. The solid circle signifies the zone boundary. All the nodes within the solid circle fall in the same zone. We use circular shapes to derive an approximate relationship; the actual shape of zone or communication range in a network need not be circular. In Figure 2(a), there is only one node in each zone (this case is equivalent to traditional Rumor Routing algorithm). Since all the nodes are neighbors of node A and are in different zones, the agent at node A can select any node (even closer nodes like D,B,F etc) with equal probability. Therefore the agent may waste its transmissions by selecting nearby nodes as next hop and may fail to spread the rumor farther in the network. In Figure 2 (b), G, E and C are neighbors of node A, but are in different zones. The agent at node A will try to select G, E or C. This decision will allow the agent to jump farther from node A and hence spread the rumor in a wider area of network. In Figure 2(c), since all nodes lie in the same zone, the agent may again select the nearby nodes with equal probability and may end up wasting some transmissions by selecting nearby nodes as next hop. It is desired to spread rumors to a large part of the network using long hops. This helps in increasing the query delivery rate and at the same time decreases the total query transmission. Longest hop distance is limited by the communication range of the transmitting node. Figure 2 illustrates that when zone size is equal to the communication range of the sensor node then it maximizes the query delivery rate and minimizes cost of query delivery. Such a zone size will allow agent to spread the rumor farther by making big leaps and at the same time decreasing redundant transmissions. If c is the communication range of the sensor node and d is the uniform network node density (number of nodes divided by total number of cells in the network, where each node occupies only one cell), then optimal zone size Z_o in terms of number of nodes in a zone can be approximated as follows

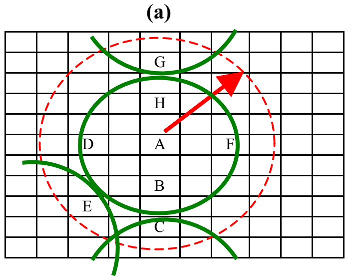
$$Z_o = \pi c^2 d$$

Therefore the optimal number of zones N_z required in sensor network of N nodes is

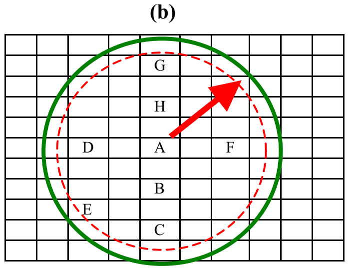
$$N_z = N / Z_o$$



(a)



(b)



(c)

Figure 2. Optimal zone size (a) When only single node is a member of each zone; (b) When multiple nodes are members of a zone (c) When all nodes within communication range of the zone leader are members of the same zone.

These results are only valid when nodes are uniformly distributed in a sensor field. It is assumed that all the zones are of same size thus it is a balanced cluster [5].

4. Simulation

A sensor network using ZRR is simulated with a simulator written in Python [12]. Each sensor node in the network has 5m communication range and 5m sensing range. Thus any node can receive packets from any other node that is at a distance within 5 m from it, as well as it can sense any event within 5m radius. Circular communication model is assumed for the simulation but it is not necessary for ZRR algorithm. Network density is varied by using constant number (4000) of uniformly scattered sensor nodes in the network grid of different sizes. Network grids of sizes {175m x 175m, 185m x 185m, 200m x 200m, 215m x 215m, 225m x 225m} are used for different network densities. Initially the network is initialized and partitioned into zones during the zone creation phase as mentioned in Section 3. Once each node has been assigned to a zone, 100 randomly scattered events were generated. Agents with TTL 1000 then spread this event in the network. After agents finish spreading the rumors, 1500 queries were generated randomly in a network. Each query is assigned a random event to search for in the network, and a TTL of queries is varied from 200 to 1500. For each case, number of queries delivered to the event source and total traffic generated to deliver queries in a network is measured.

5. Results

When the number of zones is equal to the number of nodes in the network, ZRR algorithm behavior corresponds to that of Rumor Routing. The number of zones is varied from 1 to 4000 for all the cases. Following metrics are used for evaluating the performance of the ZRR algorithm.

Query delivery rate: A query is treated as delivered when it reaches the event source. Query delivery rate is a measure of queries delivered to their requested event source as a percentage of the total number of queries generated.

Query traffic: It is a measure of total query traffic generated in a sensor network, and consists of two components: query reception and query broadcast transmission. In the ZRR algorithm, when query broadcast is done from a node, it is treated as a single query broadcast transmission. Multiple neighboring nodes can receive the query broadcast transmission, thus it is considered as multiple query reception. "Query reception" can be defined as total number of query messages received by all the nodes in a network and "Query broadcast transmission" is defined as total number of query broadcasts done by all the nodes in the network. Both query traffic components have different energy costs associated with it. These may be combined to measure the total energy consumed by the query traffic in the sensor network.

Agent traffic: It is a measure of total agent traffic generated in a sensor network for spreading the rumor of the events. It also consists of two components, i.e., agent reception and agent broadcast transmission. "Agent reception" and "Agent broadcast transmission" are defined similarly as "query reception" and "query broadcast transmission". In ZRR, number of agent broadcasts is always equal to the agent TTL. If sensor nodes are uniformly distributed in a sensor field and circular communication model is assumed for each sensor, then "Agent reception" A_r is approximated by the following expression. Let c be the communication range, d be the density of the network, N_a be the number of agents and A_{TTL} be the agent TTL then

$$A_r = N_a \pi c^2 d A_{TTL}$$

For above formula, it is assumed that nodes are uniformly distributed in the sensor field and for every agent broadcast, nodes within its communication range receive the agent.

Cost of query delivery: It is defined as the amount of query traffic generated per delivered query in the sensor network. It can be treated as a measure of the average energy consumed for every delivered query thus it is used to compare the performance of the ZRR and Rumor Routing algorithm.

5.1. Effect of number of zones on the query and agent traffic

Number of zones, and thus the zone size, may influence the performance of ZRR in terms of total agent and query traffic generated in the network. Figure 3 shows that the number of "query broadcast transmissions" and "query receptions" follows the same pattern when number of zones is changed. Number of "agent broadcast transmissions" is determined by agent TTL and is independent of the number of zones. Also, as seen in Figure 3, "agent reception" remains relatively constant and is less than both query traffic components. Number of "query receptions" is significantly higher than all other traffic components. Thus number of "query receptions" can be used as a measure energy efficiency of ZRR algorithm. As seen in Figure 3, there exists a zone size at which total traffic is significantly lower than the traffic generated by Rumor Routing algorithm.

5.2. Effect of number of zones on the query delivery rate

Figure 4(a) illustrates that query delivery rate initially increases with the increase of number of zones (i.e., as zone size decreases), and then starts decreasing. There exists an optimal value for the number of zones at which the ZRR gives the highest query delivery rate with minimum cost in terms of query traffic. When number of zones is equal to the number of nodes in a sensor network, there is only one node in each zone; therefore ZRR behavior corresponds to that of Rumor Routing algorithm. Thus in Figure 4(a) and 4(b), when number of zones is 4000, performance of ZRR is same as that of Rumor Routing algorithm. Moreover, it is also observed that ZRR, with proper selection of zone size, is capable of delivering significantly more queries than Rumor Routing under varying network densities.

5.3. Effect of zone size on cost of query delivery

In order to evaluate the efficiency of the ZRR algorithm, it is important to investigate amount of

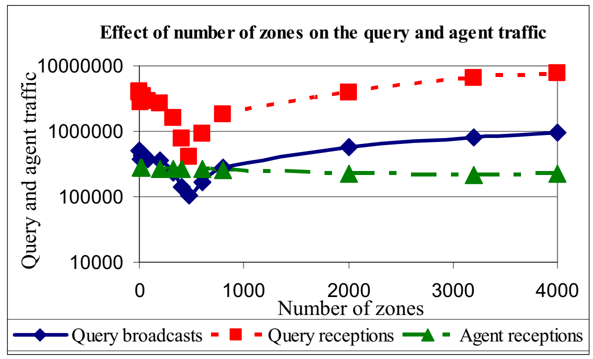
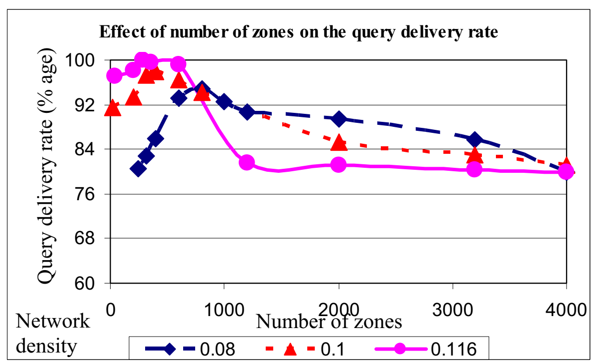
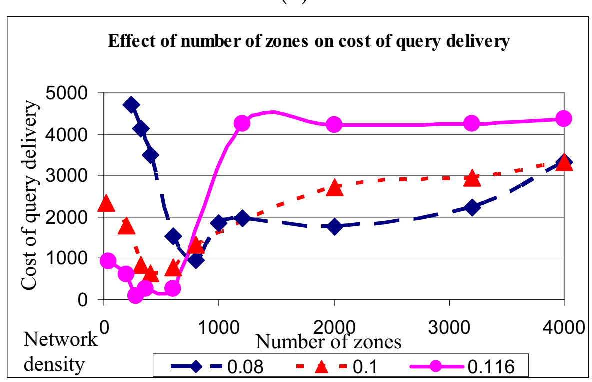


Figure 3: Effect of number of zones on query and agent traffic (Density of network = 0.1, total queries = 1500, total agents = 32)

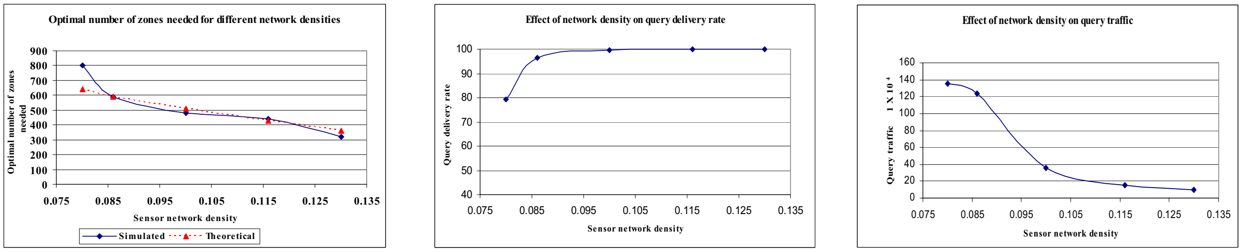


(a)



(b)

Figure 4: Effect of number of zones on query delivery under different network node densities. Number of sensor nodes is 4000, network densities are 0.08, 0.1 and 0.116. (a) Effect on query delivery rate (b) Effect on cost of query delivery



(a) (b) (c)

Figure 5: Effect of network density on (a) Optimal number of zones, (b) Query delivery rate, and (c) Total query traffic generated.

traffic generated for every delivered query. As seen in Figures 3 and 4(a), query traffic increases and query delivery rate decreases with increase in number of zones thus increasing the cost of delivery shown in Figure 4(b). When optimal numbers of zones are used for ZRR, then cost of delivery is always lower than the cost of delivery for Rumor Routing algorithm.

Experiments are performed to determine the impact of node densities on the performance of the ZRR. Figure 5(a) illustrates that when total number of sensor nodes is kept constant and network density is increased by reducing the size of the sensor field, less number of zones are required for the best performance of the ZRR algorithm. Figure 5(a) shows that theoretical value of optimum zone size as given in Section 3.2 is very close to the empirical value of the optimal zone size. The small error in theoretical optimum zone size can be attributed to the assumption about ideal uniform random distribution of sensor nodes in the network. When network density increases, the number of neighbors of each node also increases. In this case agent tends to explore the large number of node's neighbors for information about other events, thus increasing the probability of query delivery using less number of zones for dense networks. In Figure 5(b), with the increasing network density, the query delivery rate corresponding to optimal zone size increases, as nodes are closer to each other enabling the spread of the rumor to a large number of nodes. As explained before, an increase in query delivery rate will result in a decrease in query transmissions as less query transmissions will be wasted and vice-versa. This is illustrated in Figure 5(c). Thus in an environment where sensor nodes densities are changing, the zone size should be changed to get the optimal performance in terms of cost of query delivery.

6. Conclusions

This paper proposed and evaluated the Zonal Rumor Routing (ZRR) algorithm for sensor networks. The Rumor Routing algorithm [1] is a special case of ZRR corresponding to the case when number of zones is equal to the number of nodes in the sensor a network, i.e., one node is assigned to one unique one. This paper shows that ZRR algorithm performs significantly better than Rumor Routing for different network node densities when the network is partitioned into optimal number of balanced zones. In this paper it is assumed that nodes are uniformly distributed in the sensor network thus in this case optimal zone size can be computed easily. With optimal number of zones, agents and queries can cover a wider region of the sensor network with less number of hops thus increasing the probability of query delivery. It is shown that the zone size at which best performance is observed is a function of communication range and density of nodes in a sensor network. Scalability analysis has been done for networks of different densities, and it is shown that cost of query delivery decreases with increase in density. Future work will consider the optimum zone size with a non-uniform distribution of sensors in the sensor field. It is also necessary to evaluate overhead of different zone creation schemes for sensor networks.

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