Load and Energy Balanced Geographic Routing for Sensor Networks

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Abstract
In this paper, we propose a new *aggregate routing* model and a distributed aggregate routing algorithm (DARA) that implements the model for achieving load and energy balanced efficient data forwarding. DARA is designed for multi-sink multipath location aware network architecture. It's a fully distributed algorithm, each node takes routing decision based on the aggregated weight of the following three parameters: normalized geographic progress towards the destination sink, normalized delay at the candidate forwarding node and normalized residual energy. DARA selects the forwarding node that has the highest aggregated weight. We develop probabilistic models for sojourn time of a packet at intermediary nodes. The simulation results demonstrate that DARA effectively improves the energy efficiency and lifetime of the network.

Key words:
Sensor Network, Geographic Routing, energy efficiency, lifetime of a network.

1. Introduction

Efficient use of network resources is an important problem for sensor network since its scarceness of resources. By exploiting redundant paths in response to changing workload conditions and residual energy, adaptive routing has the potential for significantly improving network performance. As a result, automated mechanisms for adaptive routing have attracted significant research attention over the last few years [1] [2 [3].

Most of the existing geographic routing protocols [5][6][7] look for shortest path routing. But, this incurs additional burdens on some specific sensors only, causing the network congested and failure of nodes due to energy deficiency. Moreover, data packets converge somewhere near the sink as in Fig. 1a, which increases traffic contention and average packet delay. Therefore, we advocate that the use of multi-sink multi-path routing (Fig. 1b) is more suitable as it splits the large burst of data into smaller bursts flowing through spatially separated nodes.

In this paper, we propose a load and energy balanced geographic routing scheme that defines an *aggregate routing function* based on three metrics: geographic progress towards the destination, residual energy and expected sojourn time of a packet at the receiving node. We develop probabilistic model for sojourn time of a packet at an intermediary node. We then propose a distributed aggregate routing algorithm (DARA) that finds a forwarding node with the maximum aggregated weight. DARA does not maintain any global state information. DARA is a fully localized algorithm, *i.e.*, each sensor performs localized routing decisions, yet the collective outcome ensures almost homogeneous energy dissipation rates keeping homogeneous load sharing.

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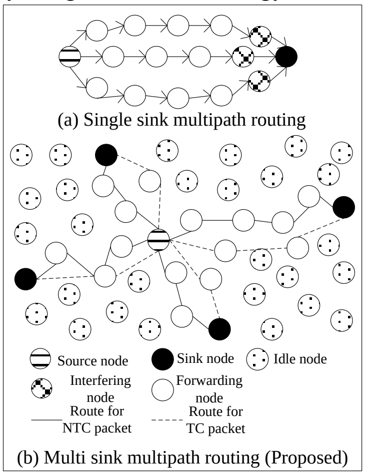
2. Related Works

In geographic routing, the most popular routing metric is the progress speed, which looks for a neighbor geographically closest to the destination [5][6][7]. This simple greedy approach gives the least hop route from the source to the destination. But, if all the packets are routed over this route, a small set of nodes will be overburdened in terms of energy and network load. Energy-aware QoS geographic routing [1], in selecting the next hop node, assigns more priority to the delay factor for emergency packets and to the energy factor for less aggressive packets. They uses single-sink multi-path routing.

MMSPEED [2] is a novel packet delivery mechanism, where routing is driven by two parameters - the geographic progress speed of a packet from node *i* to *j* towards the final destination *k*, $Speed_{i,j}^{k}$, and the end-to-end total reaching probability (TRP). In MMSPEED, node *i* forwards a packet to its downstream node *j* whose $Speed_{i,j}^{k}$ value is higher and TRP is greater than some threshold. But, unfortunately TRP is calculated on the assumptions that packet loss rate in each of the following hops will be similar to the local loss rate of the current node. Hence, the routing function of MMSPEED does not reflect the real dynamics of sensor network, where achieving energy efficiency and minimizing per node packet delay are the main hurdles of efficient routing in SN.

Multi-constrained multi-path (MCMP) routing [3] uses link delay and reliability as routing decision parameters in single-sink multipath network (Fig. 1a). Packets are duplicated at each hop by solving optimization problem. But, this approach considers neither residual energy nor progress speed. Hence, packets may get routed to a node which is highly congested and/or energy critical.



(a) Single sink multipath routing

(b) Multi sink multipath routing (Proposed)

Fig. 1. Single-sink multipath and multi-sink multipath routing.

3. Proposed Routing Model and Algorithm

The basic idea is to allow the data packets to go through the shortest route that is both load and energy balanced. DARA algorithm finds most suitable forwarder nodes towards each sink.

3.1 Network Model

We consider a densely deployed large scale sensor network in which S identical sensor nodes and M sinks are uniformly distributed (Fig. 1b). Each sensor node knows geographical locations of all sinks and its neighbor nodes. Radio transmission range (R_{tx}) of all sensors is equal and there is no hole in the network [4]. Each node has the equal initial energy ($E_{initial}$). The distance between any pair of nodes, i and j, is the Euclidian distance between them, denoted as *dist(i,j)*. Modified 802.11 MAC protocol is used. We also assume that the sinks are connected via an external network to a data collection center, which takes the controlling decisions based on the collected data packets. Therefore, it is sufficient that any of the sinks receives one copy of the transmitted packet.

Each node broadcasts BEACON messages, each after d_{beac} units of time, which carry the node's (x,y) position, residual energy ($E_{residual}$), and expected sojourn time of a packet ($E[\partial]$). These are required by the proposed routing algorithm DARA.

3.2 Modeling Sojourn Time of a Packet

We model a sensor node as an M/G/1/K queue (Fig. 2).

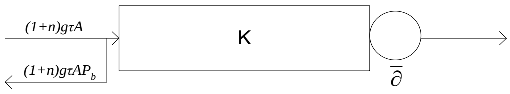


Fig. 2. An M/G/1/K model of a sensor node

Based on the assumption that events can occur anytime at any point of the network with equal probability and each event persists for τ units of time, we find the probability of occurring at least one event at a particular point of the network is equal to $g\tau$, where g be the Poisson rate of data generation at a point in the network. Thus, the data generation probability of a sensor node, within one sensing period, is equal to $g\tau A$, where A is the sensing coverage area of a sensor. We also assume n the number of total source nodes for which a sensor is forwarding data packets is Poisson distributed. Therefore, due to the superposition property of the Poisson process and the equal data generation probability of nodes, the arrival process of a node is also Poisson and it is equal to $(g\tau A+ng\tau A)$ *i.e.*, $(1+n)g\tau A$. The service time requirements have a general distribution with mean $\bar{\partial}$. The *pmf* of the total number of packets in the node has the following expression

$$P[N=n]=\frac{(1-\rho)\rho^{n}}{(1-\rho^{K+1})} \tag{1}$$

where, ρ is the traffic intensity and is equal to $(1+n)g\tau A\bar{\partial}$. An arrival will be blocked if the total number of packets in the node has reached a predetermined value K. Therefore, the service model can handle at most K packets at a given time. The probability of blocking is denoted as P_b. Hence, the rate of blocked packets is given by $(1+n)g\tau AP_b$. From Eq. (1), we can derive the following performance metrics: average sojourn time of a packet, throughput and blocking probability. Since the blocking probability P_b is equal to the probability that there are K packets in the node, *i.e.*, the node is full, it is given as follows

$$P[N=K]=\frac{(1-\rho)\rho^{K}}{(1-\rho^{K+1})} \tag{2}$$

The node throughput H is the rate of packets transmitted successfully. When the node reaches at equilibrium, H is equal to the rate of accepted packets,

$$H=(1+n)g\tau A(1-P_b) \tag{3}$$

The expected sojourn time of a packet is defined as the time from the packet insertion into the interface queue until the notification of successful transmission. It includes the queuing delay, *backoff* timeout, contention period, and retransmissions due to error or collision. Therefore, following the Little's law, we can calculate the expected sojourn time of a packet as in Eq. (4).

$$E[\partial]=\frac{E[N]}{H}=\frac{\rho^{K+1}(K\rho-K-1)+\rho}{ng\tau A(1-\rho^{K})(1-\rho)} \tag{4}$$

The parameter $\bar{\partial}$ in our model is to be estimated. We assume that the average sojourn time for a certain arrival rate can be estimated from measurements. The estimation at node *i*, $\hat{\bar{\partial}}_i$, is obtained by maximizing the likelihood function of the observed average sojourn time.

3.3 Distributed Aggregate Routing Algorithm (DARA)

Using BEACON messages each node *i* learns (*x*,*y*) position, residual energy ($E_{residual}$) and expected sojourn time of a packet ($E[\partial]$) of all neighbor nodes. Our intention is to forward data packets to a downstream node which gives higher geographic progress, lower sojourn time and/or has the higher residual energy. To accomplish this, we use *aggregated weight* of these routing metrics. We define the *aggregated weight* of a candidate downstream node as the sum of individual normalized weights of its above parameters. The node *i* calculates the normalized geographic progress of a packet towards a sink *m* for each candidate downstream node *j* as follows

$$NGPROG(i, j, m) = \frac{dist(i,m) - dist(j,m)}{dist(i,m)}.\hat{r}_{ij} \tag{5}$$

where, $\hat{r}_{ij}$ represents the estimated reliability of the link (*i*,*j*), which is measured as the ratio of the number of packets received by the downstream node *j* to the number of packets sent by the upstream node *i*. We assume that each node *i* can measure $\hat{r}_{ij}$ using the exponential weighted moving average (EWMA) formula. Note that, in Eq. (5), only the downstream nodes *j* that satisfy the condition *dist(i,m)>dist(j,m)* are considered.

The node *i* calculates the normalized residual energy for each candidate downstream node *j* as follows

$$NRE(j) = \frac{E^{j}_{residual}}{E^{j}_{initial}} \tag{6}$$

Also, the node *i* can calculate the normalized expected sojourn time of a packet at each candidate downstream node *j* as follows

$$NDELAY(j) = \frac{E[\partial_j]}{TTL_{initial}} \tag{7}$$

where, $TTL_{initial}$ is the initial TTL value of the packet to be transmitted. In our simulation, we set this value to 200ms.

Now, the problem of routing a packet from the source node to the destination sink clearly boils down to the problem of finding the downstream node that produces the maximum *aggregated weight*. The node *i*, in DARA, for delivering the data packets towards a sink *m*, respectively, finds the downstream node with maximum *aggregated weight* using the following Eq. (8).

$$DN(i,m) = \max_{j \in S^i}(\alpha.NGPROG(i, j, m) + \beta.NRE(j) + \gamma.(1 - NDELAY(j))) \tag{8}$$

where, α, β and γ are nonnegative weight factors conditioning that $\alpha>\beta>\gamma$ and $\alpha+\beta+\gamma=100$. Thus, the normalized geographic progress parameter has the highest weight while expected sojourn time gets the least weight factor. The analytical analysis and our extensive simulation results, performed in *ns-2*, conclude that for a densely deployed network, setting $\alpha=70$, $\beta=20$, and $\gamma=10$ produces the best results.

The rationale to define and maximize the *aggregated weight* function in Eq. (8) is as follows. The *aggregated weight* is a linear combination of three parameters. The first parameter $NGPROG(i, j, m)$ represents how much geographic progress a packet can make towards the destination sink *m*. In Eq. (5), the factor $\hat{r}_{ij}$ is correspond to the quality of the link (*i*,*j*). Therefore, maximizing Eq. (5) means maximizing the packet transmission efficiency. If several candidate downstream nodes have the same residual energy and expected sojourn time of a packet, maximizing Eq. (8) decreases the number of hops a packet has to travel before it reaches at the destination, which in turn decreases both the energy consumption and end-to-end packet delay. The second parameter $NRE(j)$ represents the fraction of energy available at downstream node *j*. This part contributes to ensure the balanced energy consumption by the nodes.

The third parameter $NDELAY(j)$ corresponds to the expected fraction of lifetime of a packet that may be spent at the candidate downstream node *j*. The lower the value is, the better the packet transmission efficiency is. Even though, in Eq. (8), the least weight is given to this parameter, it plays an important role in (i) achieving well traffic load distribution among the nodes and (ii) restricting a sender from delivering data packets to a highly loaded node.

Finally, the distributed aggregate routing algorithm (DARA) that finds the downstream nodes for each sink is presented below.

DARA Algorithm

At each node, i:

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Initialization:
    for each sink m
        DN_TC(i,m) = φ and DN_NTC(i,m) = φ
    broadcast BEACON message

loop
wait (until node i receives a BEACON message
        from some neighbor j)
Add node j to S^i
 for each sink m
calculate NGPROG(i,j,m), NRE(j) and NDELAY(j)
using Eq.(5),Eq.(6) and Eq.(7)
    update DN(i,m) using Eq.(8)
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if (node i finds that it has to send BEACON msg., i.e., d_beac expires)
broadcast BEACON message
forever
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4. Simulation Results

We have performed extensive simulations in *ns-2*. We compare MMSPEED [3] and MCMP [4] with the proposed load and energy balanced DARA algorithm, in terms of the following performance metrics.

- *Energy efficiency* (η): It is measured as the ratio of total consumed energy by all nodes to the number of packets received by sinks. Note that in this case, the higher the value is, lower the efficiency is. Also, (1- η) gives the energy efficiency in terms of residual energy and in this case, the higher the value is, the better the transmission efficiency is.

- *Standard deviation of energy consumption* (σ_e): It gives the average variance between the residual energy levels on all nodes. This metric indicates how well the energy consumption is distributed among the sensor nodes. The smaller the value is, the better the capability the routing protocol has in balancing the energy consumption.

The simulation parameters are described as follows. 1000 sensors and 4 sinks are uniformly distributed over the area of 1000m x 1000m. Sensor nodes and sinks are stationary. The value of R_{tx} is chosen 100m and data transmission rate is 512kbps. Initial energy of each node is 5 Joule and the payload size is 32 bytes. The buffer at each node can hold at most 30 data packets. The simulation is run for 5 minutes and each event lasts for 50 seconds. During an event, 100 nodes are randomly selected as source nodes, each of them generates packets at the rate of 4 pkts/sec.

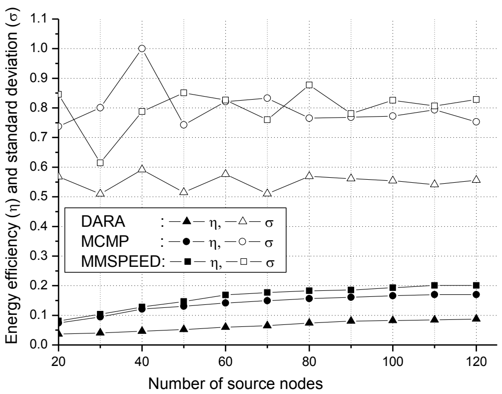

Fig. 3. Energy efficiency and standard deviation of energy consumption

As shown in Fig. 3, DARA is energy efficient as compared to others. This is due to the use of power-aware transmission and reduced number of retransmission. Furthermore, DARA reduces the standard deviation of energy consumption by using residual energy of target node as routing metric, which in turn increases the network lifetime.

5. Conclusions

The proposed routing mechanism is load and energy driven; therefore network nodes would not be overshooted with high traffic as well as the network lifetime would be longer. It optimizes the tradeoffs between the shortest route and homogeneous node utility while improving the spatial balance of energy burdens. We are now working on the robustness and optimality of adaptive algorithms in sensor networks.

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