Energy-Efficient Greedy Forwarding Protocol for Wireless Sensor Networks

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***Abstract*—In a wireless sensor network, as the sensor nodes have limited energy, it is important to minimize nodal energy consumption due to message communication to extend the network lifetime. Existing forwarding protocols either do not consider network performance and energy saving jointly, or they are not distributed. In this paper, we propose a hybrid approach, called minimum consumption maximum remaining energy (MIN-MAX-E) forwarding, which combines minimum energy consumption of transmitter-receiver pair along with maximum remaining energy of the receiver in making a relay node selection decision. Extensive simulation studies show that the proposed algorithm offers a significantly improved energy saving performance with respect to the existing energy-aware approaches.**

I. Introduction

Wireless sensor network (WSN) consists of small sensor nodes that are usually provided with limited battery power and memory resources. Due to the difficult environments and the scale of deployment, recharging or replacing the sensor nodes' batteries is not feasible. Since there is a high cost associated with network maintenance caused by frequent battery drainage, energy saving in a WSN to optimize its lifetime has drawn significant attention to the researchers. To this end, several alternate energy-efficient protocol techniques across the functional layers have been proposed to reduce the energy consumption of nodes and hence to increase the nodal as well as overall lifetime of the network. Among different routing and forwarding strategies, distributed data forwarding approaches are quite useful for multihop wireless communication due to the low overheads associated with it.

In a distributed forwarding scheme a transmitter chooses a best relay node based on the local information. The relay selection criteria could depend on such parameters as the amount of energy the relay would consume, remaining energy at a forwarding candidate node, distance progress toward the destination, link quality between the transmitter and receiver, buffer size at the receiver, etc. These techniques can be applicable to individual optimization criterion, such as increase in nodal lifetime, increase in network lifetime, reduction in end-to-end delay, increase in network throughput.

In a wireless channel, the signal power decreases following power law as the distance between transmitter-receiver increases, which causes decrease in signal-to-noise ratio (SNR) and hence increase in packet error rate (PER). In pure geographic greedy forwarding [1], the optimization criteria used minimizes the hop count between the source and destination. Although this may help minimize the end-to-end delay, it is not optimal in terms of throughput and energy consumption, as it will require more number of retransmissions to successfully transmit a packet. Some other energy-aware routing protocols consider either only transmitter energy consumption [2], [3], or transmitter-receiver energy consumption without accounting the channel errors [4], or energy minimization without allowing distributed control [5].

In a pure energy-aware greedy protocol, at every hop the nearest node to the transmitter will be selected as the forwarder, as it offers the lowest average number of transmissions per successful packet forwarding. In addition, if the remaining energy of the neighbor node is also considered, then the highest remaining energy node will be selected among the nearest nodes [6]. No significant performance gain can be achieved if conversely the minimum energy consuming node is selected from the set of highest remaining energy nodes [7]. Our prior work [8] considered a forwarding criteria that minimizes transmitter and receiver energy consumption along with maximizing Euclidean distance progress towards the destination, where we defined a normalized measure called energy consumption per successful packet forwarding per unit Euclidean distance progress, E_c. In that approach, a transmitter would select a relay having minimum E_c value. However, in this approach if the selected node has lesser remaining energy then the node may die down quickly, possibly leading to an early network partition. So, in addition to considering the nodal energy consumption in a successful forwarding, one should also consider the remaining energy of the receiver.

Motivated by the above observations, in this paper we propose a hybrid energy-aware forwarding strategy, called minimum consumption maximum remaining energy (MIN-MAX-E) forwarding. We compare the link layer throughput and energy saving performance of the protocol with the other greedy and energy-aware forwarding strategies where a relay node is selected using different heuristics. Our simulation studies show that our approach outperforms the other protocols in terms of network lifetime and link layer throughput.

The rest of the paper is presented as follows. The related works are surveyed in Section II. The proposed MIN-MAX-E protocol operation and its performance analysis is presented in Section III. Section IV contains simulation based performance results. The paper is concluded in Section V.

II. Related Works

In a simple location aware forwarding where a transmitter node at each hop has the location information of its local neighbors as well as the destination, one may try to minimize the number of hops to the destination by advancing as much distance as possible toward the destination (called, least remaining distance (LRD) forwarding) [1], [9]. GeRaF is another such location aware end-to-end delay minimizing technique in a dynamic sensor network [10], where the forwarding relay is selected (with a receiver contention scheme) and maintained for next T seconds. However by choosing a relay node which minimizes the distance to the sink, the transmitter-receiver distance increases which leads to increase in PER and hence more energy will be consumed due to retransmissions.

In some energy-aware forwarding protocols [11], [12], [13], appropriate cost values are assigned to the forwarding neighbors based on certain criteria. While in [11], [12] a product of PER and distance progress was used as the cost function, in [13] the cost function optimization was studied to minimize the average number of retransmissions and at the same time maximize the distance progress. However these approaches did not consider nodal remaining energy as a constraint.

A few forwarding approaches did consider remaining energy at the receiver. A probabilistic energy-aware routing (which we call PEAR) protocol was proposed in [6], where a cost function was defined considering the energy consumption of transmitter-receiver as well as the remaining energy of the receiver. By assigning probabilities to the nodes proportional to their cost value a node is selected randomly at each hop. An improvised scheme over PEAR, called maximum remaining energy - directed diffusion (MRE-DD), proposed in [7], first selects a set of highest remaining energy nodes and among them chooses the one which would offer minimum energy consumption. Unlike PEAR, where a node selection is probabilistic, MRE-DD is a deterministic selection protocol. Although selection process of MRE-DD is different from PEAR, the former gives comparatively better performance in terms of network lifetime. However, both schemes end up selecting a much longer route (in terms of number of hops), as they tend to select a relay node closer to the transmitter, thereby consuming more energy for routing. Probabilistic geographic routing (PGR) ([14]) is another such protocol which assigns probabilities to the neighbor nodes according to their ratio of remaining energy and average number of retransmissions required. Thus, probability of a node being selected as the forwarder is higher if it has higher energy left and number of retransmissions is less. PGR almost follows PEAR in selecting a relay node in the same nearest zone, which effectively leads to its higher end-to-end energy consumption. A recent greedy minimum energy forwarding protocol, called GMFP ([8]), combined the greedy geographic forwarding node selection, transceiver energy consumption, and link layer retransmissions in data forwarding decision making at each hop.

In our current work, we improve upon the approach in [8] by including the effect of remaining energy at a potential forwarder in the relay selection criteria. The cost function in the proposed MIN-MAX-E enables a node selection from among the ones offering minimum E_c (energy consumption per successful packet per unit Euclidean distance progress) and having maximum remaining energy. The proposed approach helps jointly increase the network throughput and lifetime, while incurring some trade off in terms of increased hop count and hence end-to-end delay.

III. The Minimum Consumption Maximum Remaining Energy (MIN-MAX-E) Forwarding Protocol

A. Background and definitions

In a distributed forwarding strategy, a transmitter – which could be the source or an intermediate node along a route – at each hop has to select one potential relay node based on the locally available information. To effect this, each potential forwarding node is assigned a cost, which may be different in different forwarding strategies. The best forwarding neighbor is selected at each hop until destination is reached.

Before we proceed with a specific forwarding strategy, we define some useful terms in the following:

1) Node j is said to be a *potential forwarding neighbor* of node i iff the distance to the destination from node j is less than that from node i.
2) *Received power* $P_r(r)$ at a distance r is:
$$P_r(r) = \kappa \frac{P_t}{r^\gamma}, \quad (1)$$
where P_t is the transmitted signal power, γ is the power law decay factor which varies between 2 and 6, and κ is a proportionality constant which depends on the transmit and receive antenna properties [15, Ch. 4].
3) *Packet error rate (PER)* $p_p(r)$ is the probability of a packet being dropped due to physical layer link error. $p_p(r)$ depends on bit error rate (BER) $p_b(r)$ which in turn is a function of signal-to-noise ratio $SNR(r)$, where r is the transmitter-receiver distance. We have:
$$p_p(r) = 1 - \sum_{i=0}^{l} \binom{L}{i} \Big(p_b(r)\Big)^i \Big(1 - p_b(r)\Big)^{L-i}, \quad (2)$$
where, for BPSK signal, $p_b(r) = \frac{1}{2}\text{erfc}\Big(\sqrt{\text{SNR}(r)}\Big)$.
4) *Average number of retransmissions* is the expected number of attempts $N_a(r)$ for successful delivery of a packet to the next node. Assuming infinite retries possible,
$$N_a(r) = \frac{1}{1 - p_p(r)}. \quad (3)$$
5) *Energy consumption per successful packet forwarding* E_s is the total energy spent in successful transmission of a packet to the next node, which is given by,
$$E_s(r) = N_a(r) \cdot (e_t + e_r), \quad (4)$$
where e_t and e_r are the energy required at the transmitter and receiver, respectively, per transmission attempt.

6) *Energy consumption per successful packet per unit Euclidean distance progress,* E_c is given by,

$$E_c(r) = \frac{E_s(r)}{d_p}, \tag{5}$$

where d_p is the distance progress from the current transmitter toward the destination. Let r_a is the distance of the node A from the transmitter, and θ_a is the angle between A and the baseline joining the transmitter and the destination (cf. Fig. 2). Then, $d_p = r_a \cos\theta_a$.

7) *Normalized distance progress* $\tilde{d}_p$ is the ratio of distance progress d_p and communication radius R.

8) *Normalized remaining energy* $\tilde{E}_i^{(r)}$ of node i is the ratio of remaining energy of the node to its initial energy.

B. Selection zones

Figure 1 shows the relation between normalized energy consumption E_c and one hop Euclidean distance progress. It is clearly evident that a forward direction node which offers either too small or too large distance progress toward the destination tends to consume more network energy. Because, at a very large transmitter-receiver distance more energy is consumed due to retransmissions, and if the distance progress is too small the strategy eventually consumes more network energy due to higher number of hops. Hence, a trade off should be achieved wherein a node may have about an average forward progress but offers a smallest possible E_c.

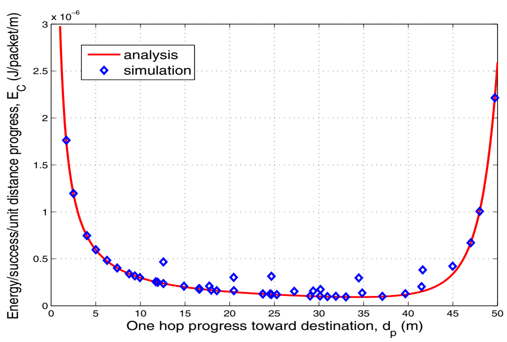

Fig. 1. Normalized energy consumption versus Euclidean distance progress. In simulation, average number of neighbors = 100.

C. MIN-MAX-E Forwarding

Our proposed MIN-MAX-E forwarding aims at maximizing the *network lifetime* and increasing *throughput performance* by choosing a most suitable relay node at each forwarding stage.

To model and characterize the relative performance of MIN-MAX-E forwarding with respect to the other competitive strategies, we make the following simplifying assumptions.

- Sensor nodes are uniformly random distributed.
- Nodes are aware of location information of local neighbors and the destination.
- Forwarding is purely stateless; a priori knowledge of end-to-end route is not available.
- Routing holes can arise only due to lack of nodal energy.
- Although the relay selections may be deterministic, the link-level error performance is unpredictable due to wireless channel dynamics.
- A packet error is a function of channel state only and not dependent on MAC conflicts.

To have a better understanding on the optimum forwarding distance per hop, we virtually divide the forward direction area of a transmitter T into three zones: *near*, *middle*, and *far* (Fig. 2). The computation for a relay node selection is based on static information (distance between two nodes) and long-term average statistics (noise and interference). In a greedy geographic LRD approach, T will tend to select a node from the *far zone*, say the node C. By the E_c criteria in GMFP [8], T will tend to select a node from the *middle zone*, say a node A or B. Let both A and B have nearly the same link quality (measured by $p_p(r)$). In this case, since A offers a higher $\tilde{d}_p$, A has a lower E_c. On the other hand, A and E may offer the same $\tilde{d}_p$, but A will have lesser E_c. Hence, in GMFP, A will win over the node B and E. Instead of E_c, if a relay node selection is based on E_s, or if it is based on minimum E_s and maximum remaining energy of the relay node (as in [6]), then the probability of choosing a node in the *near zone* is higher. Clearly from Fig. 1, PEAR may end up choosing a node with a high E_c. MIN-MAX-E protocol looks for maximum remaining energy nodes from among the minimum E_c nodes, thereby it will likely select a node in the *middle zone*.

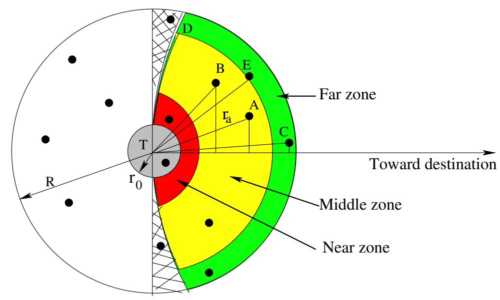

Fig. 2. Forwarding approach dependent node selection zones.

Since MIN-MAX-E is a stateless and distributed strategy, in this paper we conduct studies on link layer performance only. The following performance criteria are considered:

Performance criteria 1: Maximize throughput (η) $\times$ normalized distance progress ($\tilde{d}_p$).

Performance criteria 2: Minimize energy consumption per unit distance progress, $\frac{E_s}{\tilde{d}_p}$.

Performance criteria 3: Maximize network lifetime τ_l, defined as the time until a node fails to find a forwarding node caused by the energy depleted all forwarding neighbors.

D. Defining cost functions

We consider GMFP, LRD, PEAR, and MAX-RE (maximum remaining energy) protocols in addition to the proposed MIN-MAX-E forwarding for relative performance modeling. We model the performance as a cost maximization problem where the node having maximum cost will be selected. Functions for assigning the cost to a relay node i can be defined as follows:

1) *LRD forwarding*: The cost function associated with LRD forwarding is $C_i = d_{p_i}$.
2) *GMFP:* The cost function in GMFP is $C_i = E_{c_i}^{-1}$.
3) *PEAR* assigns the cost to each relay node according to $C_i = E_{s_i}^{-1} \cdot \tilde{E}_i^{(r)}$.
4) *MAX-RE* has the cost function as $C_i = \tilde{E}_i^{(r)}$
5) *MIN-MAX-E* assigns cost to the forwarding neighbors in such a way that the relay node which offers minimum E_c and also has higher energy left in it, will be selected. Accordingly, the cost function is: $C_i = E_{c_i}^{-1} \cdot \tilde{E}_i^{(r)}$

E. Ideal distance of the forwarding neighbor

As evident from Fig. 1, $E_c(r)$ has a global minima. The value of r at which it attains its minima, can be achieved by taking derivative of $E_c(r)$ with respect to distance r as:

$$\frac{dE_c(r)}{dr}\bigg|_{r=r_{ideal}} = 0 \tag{6}$$

Numerically obtained as well as simulated ideal distance of a relay node for minimum E_c is found nearly as $0.7R$ (Fig. 3).

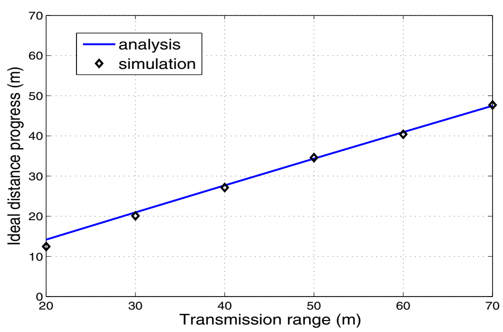

Fig. 3. Ideal distance of a relay node. Average number of neighbors in simulation is 100.

IV. Simulation Results and Discussion

Our performance evaluations have been carried out via MATLAB based discrete event simulations. In a 700 m $\times$ 700 m area we deployed sensor nodes uniformly randomly with a fixed network density, ρ of 0.015. To have a BER $\leq 10^{-3}$, transmit power (P_t) for different transmission radii (20 m to 70 m) were calculated by using two-ray ground propagation model with a fixed receiver threshold of -86 dBm and long-term average noise power -86.7 dB. Sensor node specifications were taken from Chipcon RFIC datasheet (www.chipcon.com/files/CC2420_Data_Sheet_1_4.pdf). Log-normal channel fading was simulated with a 4 dB standard deviation. BPSK modulation with NRZ signal was considered. Fixed packet size of $L = 320$ bits was taken and the number of recoverable bit errors was taken $l = 16$ with the transmission time of the packet being 4.21 ms. These values correspond to the existing standard coding mechanism. The initial energy of each node was taken as 100 mJ. To avoid the boarder effects, only the nodes within inner $(700 - R) \times (700 - R)$ region were considered for selecting transmitter and receiver nodes. Sufficient simulation runs were conducted with varying seed values to have a confidence level of 95% within the range of $\pm 2\%$ of the results obtained.

Network performance results were taken by generating traffic between randomly chosen source-destination pairs. The network is said to be partitioned at an instant when a transmitter finds that none of its forwarding neighbors have sufficient energy to forward a packet. Network lifetime for different forwarding strategies were measured by the simulation time until the network was partitioned.

In Fig. 4 the throughput performances for difference values of R are shown. In almost all cases (except for LRD) the plots are flat, which is because we have taken a fixed receiver threshold for different values of R. For example, a node which is at a distance of 15 m from the transmitter with $R = 20$ m will give a throughput performance same as in the case when a node is at 30 m distance from the transmitter with $R = 40$ m. Also, the normalized distance progress is same for both cases. However in LRD forwarding the throughput decreases because, as LRD always tries to select a furthest away node the mean value $\tilde{d}_p$ tends to increase with increase in number of neighbors (increase in R).

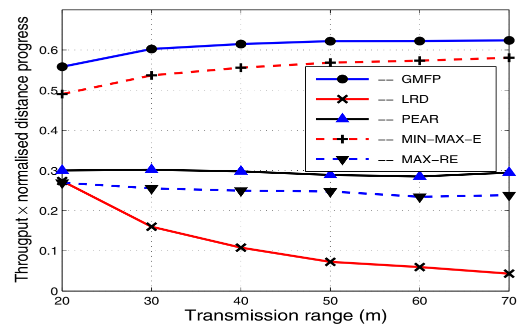

Fig. 4. Fair throughput comparison of different protocols.

Fig. 5 demonstrates the benefit of MIN-MAX-E forwarding in terms of reduced energy consumption along the active routes, where it shows that the MAX-RE and LRD protocols have significantly higher energy consumption. This has an impact on the network lifetime, which is shown in Fig. 6.

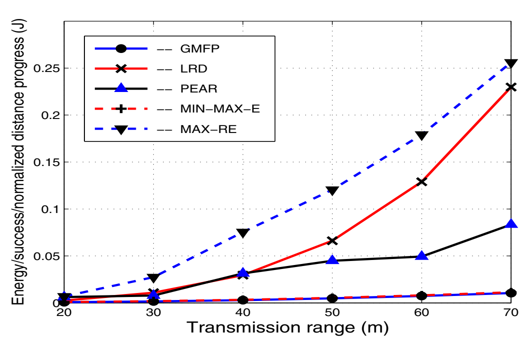

Fig. 5. Per packet energy consumption, at different values of R.

Fig. 6 shows that although compared to MIN-MAX-E,

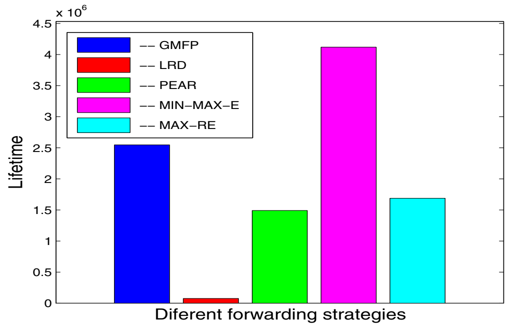

Fig. 6. Network lifetime in terms of the simulation time. R=50 m.

GMFP has a little better throughput performance, MIN-MAX-E offers about 75% higher network lifetime over GMFP as the former selects the nodes more intelligently. LRD protocol has the worst performance because of its energy unawareness.

Finally, the one hop distance progress is compared in Fig. 7. Observe that, PEAR selects relay node from the *near zone*,

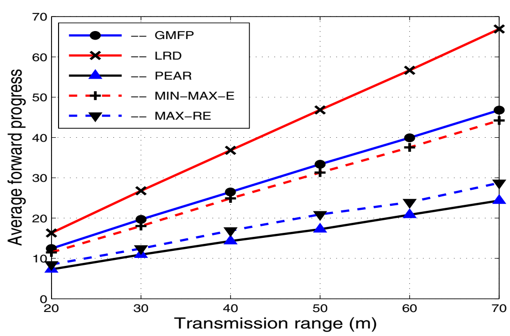

Fig. 7. Average progress at various transmission radii R.

LRD chooses from the *far zone*, whereas GMFP and MIN-MAX-E forwarding select from the *middle zone*. Although both GMFP and MIN-MAX-E protocols give a little less per-hop distance progress, the network lifetime results shown earlier indicate that, even with a larger average hop count the network would be long-lived by the MIN-MAX-E protocol.

To see the impact of node density, we have also conducted studies by varying the average number of neighbors with a fixed communication radius. But we observed approximately negligible or zero impact of node density on the performances, and hence these plots are omitted here.

V. Conclusion

In this paper we have investigated a hybrid, energy-aware forwarding strategy in wireless multihop sensor networks, where the forwarding node selection criteria is locally optimized based on minimum energy consumption greedy forwarding and nodal remaining energy. Our proposed protocol selects a forwarding node which is expected to consume minimum energy per successful packet transmission per unit Euclidean distance progress toward the destination and has a highest possible remaining energy. We have contrasted the performance of the proposed protocol with the other competitive greedy geographic forwarding techniques. We have shown that, by jointly considering the one-hop progress, transmit and receive energy consumption, and remaining energy of the receiver, the network performance can be improved significantly in terms of throughput as well as network lifetime, although the route length could be a little longer.

We plan to conduct performance studies at higher functional layer (end-to-end level) and analyze the impact of the proposed protocol on multiple simultaneous communications.

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