A Greedy Minimum Energy Consumption Forwarding Protocol for Wireless Sensor Networks

Bighnaraj Panigrahi†, Swades De†, and Jean-Daniel Lan Sun Luk‡
†Electrical Engineering Department, Indian Institute of Technology – Delhi, India
‡Université de la Réunion, Laboratoire d’Energétique, d’Electronique et de Procédés, Saint Denis, Réunion, France

***Abstract*—Energy consumption is a vital resource to be controlled to extend the longevity of a wireless sensor network. In a multihop routing, lifetime as well as throughput of the network could be increased by selecting the forwarding node intelligently. The existing energy-aware routing protocols either do not jointly consider the network performance and energy saving, or they are not distributed. In this paper, we propose an efficient greedy forwarding protocol, called minimum energy consumption forwarding, which selects a forwarding node on the basis of minimum transmit and receive energy consumption per successful packet transmission per unit Euclidean distance progress toward the destination, in a distributed fashion. In the proposed algorithm, at each hop the forwarding decision can be either taken by the transmitter at each forwarding node or the best forwarder can be elected by some kind of election contention mechanism. Through network simulations we have shown that the proposed energy consumption minimizing distributed forwarding strategy outperforms the greedy geographic forwarding algorithm in terms of increasing the network lifetime and end-to-end throughput. The proposed algorithm can be easily retrofitted in the already developed network capable wireless sensor nodes.**

Key words – wireless sensor network, greedy minimum energy consumption forwarding, location aware protocol, energy aware protocol, network lifetime

I. INTRODUCTION

In a wireless sensor network (WSN), sensor nodes are usually large in number and they are provided with limited battery power. Also, as they are generally deployed in remote and dangerous environments, it is difficult to recharge their batteries. The constraint of limited energy of the sensor nodes has drawn attention of many researchers in the recent several years. Numerous alternate energy efficient protocol techniques across the functional layers have been proposed to reduce the energy consumption of nodes and hence to increase the individual as well as overall lifetime of the network. Several distributed data forwarding schemes have been proposed for multihop wireless communication, where a transmitting node chooses a best forwarding node from its local neighbors to transmit a data packet. The criteria for choosing a forwarding node could be based on such parameters as remaining energy at the forwarding candidate node, energy consumption, packet advancement toward the destination, quality of the link to the next node, etc. Each of these techniques are motivated by individual optimization criterion, such as increase in nodal lifetime, increase in network lifetime, reduction in end to end delay, increase in network throughput, etc.

In a wireless channel, the signal power follows a power law decay as it propagates away from the transmitter. So, at each hop in a multihop forwarding, a longer transmitter-receiver distance implies a lower signal-to-noise ratio (SNR), causing a higher bit error rate (BER) and hence a higher packet error rate (PER). In traditional geographic greedy approaches [1], [2], since the optimization criteria is minimizing the hop count – which may help minimize the end-to-end delay, it may not be optimal in terms of throughput and energy consumption. The energy aware routing protocols on the other hand address either transmitter energy consumption along the route [3], [4], or transmitter-receiver energy consumption without accounting the channel errors [5], or energy minimization without allowing distributed control [6]. Transmit power control based energy saving measures have also been addressed in the literature, which is however not the focus of study in our current work.

The effect of different forwarding strategies on the probability of a forwarding node selection is demonstrated in Fig. 1, where the simple cases of pure greedy geographic forwarding [1], [7], pure link quality aware forwarding, and link quality aware greedy geographic forwarding are considered [8], [9], [10]. Clearly, in a sensor network with location aware nodes,

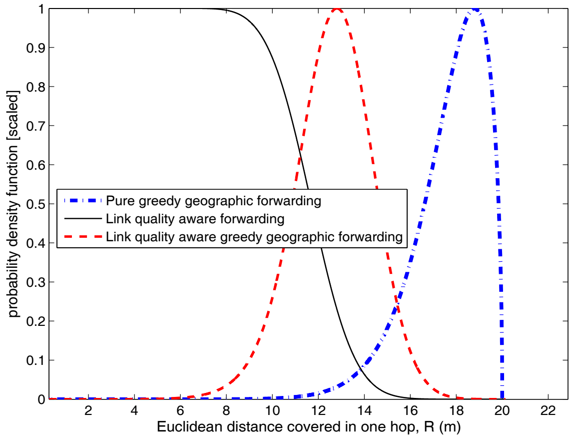

Fig. 1. Forwarding protocol dependent probability of selecting a forward direction node with respect to its distance from the current transmitter.

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these protocols can be employed distributedly. However, neither of them guarantees if the end-to-end route selected would be a minimum cost one in terms of energy consumption per successful delivery.

In this paper, we address the energy consumption minimization and throughput maximization issues in a distributed control multihop wireless ad hoc sensor network by accounting the wireless channel error properties in the data transmission process. Our proposed greedy minimum energy consumption forwarding protocol (GMFP) is compared with the greedy geographic routing protocol to demonstrate the performance gain. We show that, if the forwarding nodes are chosen by taking into account the distance progress as well as the transmit and receive energy consumption of the nodes due to possible channel errors, the lifetime and throughput of the network could be increased. Our results show that GMFP offers higher end-to-end throughput and network lifetime with respect to the greedy geographic forwarding. GMFP however has a higher average hop count, which may reflect in a longer end-to-end delay performance. Thus, in a sensor network, where delay is mostly not a critical performance criteria, GMFP can be a promising energy saving forwarding approach.

The rest of the paper is presented as follows. The related prior works pertinent to our proposed protocol are briefly surveyed in Section II. The proposed minimum energy consumption forwarding protocol operation and its performance analysis is presented in Section III. Section IV contains simulation based performance results and discussion. The paper is concluded in Section V.

II. RELETED WORKS

In a location aware greedy forwarding technique, the task is to choose an optimal next node among the forward direction neighbours so as to optimize the network performance in terms of either end-to-end delay, or network lifetime, or end-to-end throughput, or end-to-end energy consumption along the route, etc., or a combination of them. A pure greedy geographic forwarding [1] (also called least remaining distance (LRD) forwarding [7]) offers to minimize the end-to-end delay by choosing an end-to-end route with a minimum hop count. A pure geographic greedy forwarding however does not aim at maximizing the network lifetime as well as network throughput. Some distance dependent loss aware greedy geographic forwarding protocol variants were proposed in [8], [9], [10]. They tend to choose a forwarding node that offers the best of link quality and distance progress in terms of the maximum product of BER or PER and the distance progress to the final destination. These works did not study if the simple product of link quality and distance progress would give the best forwarding node. The optimality criteria was studied in [11], where it was shown that, by assigning a proper cost factor to the link quality with respect to the distance progress cost an optimal condition can be found that offers the least number of average retransmissions required per hop. The authors however did not investigate the end-to-end energy consumption and network lifetime issues.

On the other hand, there have been several forwarding protocols that were proposed primarily in the energy awareness context. One of the early works in [3] proposed a power aware routing protocol that minimize the transmission energy cost for end-to-end route in mobile ad hoc networks. The work in [5] included the receiver energy consumption as well in defining the minimum cost link metric. However, the effect of physical channel error probability was not accounted in defining the cost metric. The minimum energy path finding approach proposed in [12] considered link quality as a criteria for route selection. Hop-by-hop retransmissions were also accounted in the cost metric. It also studied the routing performance with and without transmit power control. However, the geographic greediness as well as receiver energy consumption did not play a role in their proposed variants of energy consumption optimization algorithms. The work in [4] extended the idea of minimum energy routing by taking into account the energy consumption due to medium access control (MAC) layer control packet exchanges. This approach did not take the receiver power consumption and link quality in defining the minimum energy routes.

The other existing minimum energy consumption routing algorithms (e.g., [13], [14], [15]) have proposed to adjust the transmit power according to the proximity to the chosen receiver. While the approach in [13] suffers from scalability problem, the energy consumption performance in [14] is affected due to its revision parameter in the cost function. [15] uses the ideal optimal minimum energy consumption routes to guide the routing procedure but this too does not consider the SNR value of the received signal at the receiver which affects the packet dropping rate significantly.

Our proposed GMFP stands out with respect to the existing works in that, we aim at combining the greedy geographic forwarding node selection, transceiver energy consumption, and link layer retransmission possibility due to poor link quality in our hop-by-hop data forwarding decision making process. This approach helps jointly increasing the network throughput and lifetime, while incurring some trade off in terms of increased hop count and hence end-to-end delay.

III. PROTOCOL PERFORMANCE MODELING

A. The protocol

The proposed greedy minimum energy consumption forwarding protocol (GMFP) aims to increase the *network lifetime* and *end-to-end throughput* by choosing a most suitable or eligible forwarding node at each forwarding hop.

The protocol operation and its performance model is based on the following implicit assumptions:

1) *Random node distribution:* The sensor nodes are uniformly randomly distributed in a given location space.
2) *Location awareness:* All nodes are assumed to have some kind of location awareness, which could be geographical or virtual (i.e., relative). The nodes have the local neighborhood location information based on some kind of periodic beaconing. The source node in an end-to-end data transfer has the location knowledge of the destination (which could be a sink node).
3) *Uncorrelated neighboring nodes' channels:* The channel state from the current transmitter to a forward direction

neighbor does not reveal any information of the channel state of the transmitter to another forward direction neighbor.

4) *Packet error due to wireless channel only:* A packet error is a function of channel state only and not dependent on MAC conflicts.
5) *Memoryless channel errors:* An error in the current instant does not have any bearing on the future channel state.
6) *Drop packet in case of irrecoverable error:* If a packet failure occurs at any stage along the route, it is immediately discarded.
7) *State-less routing:* A packet from the source is forwarded to the next hop based on the local information and computation only. There is no provision for end-to-end route searching before a packet transmission.

Definition 1: One-hop throughput, η is defined as the probability of successfully delivering a packet to a next hop neighbor.

Definition 2: Network lifetime, τ_l is defined as the time until a node fails to find a route to the destination caused by all forwarding neighbors' depleted energy.

To uniquely capture the distributed protocol operation, we define a performance measure: *energy consumption per successful packet per unit progress*, E_c, that is locally computed by the current transmitter at each forwarding stage for all forward direction neighbors. The neighbor offering the minimum of E_c wins to be the forwarding node. In actual protocol operation, in case of more than one neighbors qualifying the criteria, one can be chosen based on some tie break rule, such as maximum remaining energy, or minimum queue length, etc.

Definition 3: If $\eta_i^{(1)}$ is the throughput in the i-th hop offered by a forwarding neighbor that guarantees minimum E_{c_i}, i.e., $E_{c_i}^{(\text{min})}$, then the *end-to-end throughput* for an h hop route is given by: $\eta^{(h)} = \prod_{i=1}^{h} \eta_i^{(1)}$.

The protocol operation is illustrated diagrammatically in Fig. 2. All forward direction nodes in the right unshaded region of the current transmitter T are the forwarding contenders. Let us assume that at a particular forwarding stage three nodes A, B and C are the potential forwarding nodes of T. According to the greedy geographic LRD approach, node C will be chosen as it offers the least remaining distance to the destination, although it is likely to consume higher E_c. Let the nodes A and B have nearly the same link quality. But, since the node A offers a higher distance progress to the destination, A has a lower E_c, and hence it will win over the node B. The computation of forwarding node selection is done based on static information (distance between two nodes) and long-term average statistics (noise and interference power).

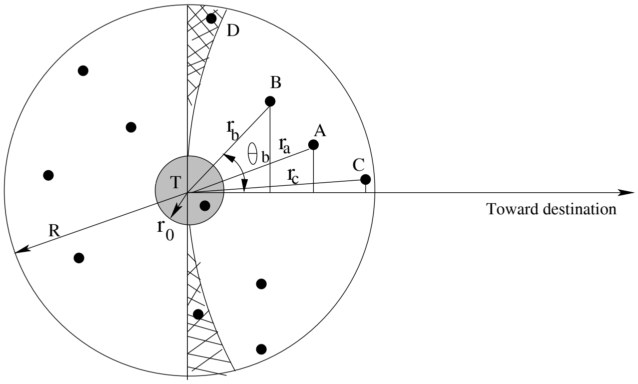

Fig. 2. Distributed decision making for a minimum energy consumption forwarding node selection.

For the protocol operation in terms of choosing the next forwarding neighbor, and for performance modeling, some points need to be considered, such as signal error condition due to wireless transmission and energy consumption.

B. Signal error condition

In a wireless transmission, the electromagnetic signal power undergoes a power law decay with distance, such that, the receive power at a distance r from the transmitter can be expressed as: $P_r(r) = \overline{\kappa}\frac{P_t}{r^\gamma}$, where P_t is the transmitted signal power, and γ is the power law decay factor, which varies between 2 and 6. The constant of proportionality $\overline{\kappa}$ is a function of transmitter and receiver system parameters, and is given by [16, Ch. 4]:

$$\overline{\kappa} = \frac{r_0^\gamma}{\text{PL}[r_0]}$$

where r_0 is called the reference distance[*] and $\text{PL}[r_0]$ is the fixed loss up to the distance r_0, and is given by, $\text{PL}[r_0] = \frac{16\pi^2 r_0^2 L}{G_r G_t \lambda^2}$. G_r and G_t are the gains of the receiving and transmitting antennas respectively, λ is the radio frequency signal carrier wavelength, and L is the system loss factor. Accordingly, the receive signal power at a r distance away receiver is given by:

$$P_r(r) = \frac{P_t r_0^\gamma}{\text{PL}[r_0] r^\gamma} \tag{1}$$

Denote $\mathcal{N}$ as the total Gaussian noise and interference power at the receiver, where the interference signal from other multiaccess users is also approximated as Gaussian. Based on the distance dependent received average signal power and the noise power, a forward direction neighbor can calculate its SNR as: $\text{SNR}(r) = \frac{P_r(r)}{\mathcal{N}}$, or, $\text{SNR}(r)$ [dB] $= P_r(r)$ [dBm] $-$ $\mathcal{N}$ [dB]. Considering BPSK modulated signal, BER at the receiver can be calculated as:

$$p_b(r) = \frac{1}{2}\text{erfc}\Big(\sqrt{\text{SNR}(r)}\Big) \tag{2}$$

C. Distributed computation of energy consumption

From the calculated BER $p_b(r)$, every forward direction neighbor of the transmitter computes the energy consumption per successful packet per unit forward progress, $E_c(r)$, as follows.

To this end, we consider constant sized packets with an (L, l) coding scheme, where L is the total packet size in

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[*] Reference distance r_0 is larger than the far field (or Fraunhofer) distance r_f, because below the distance r_f there is coupling between the transmitter and receiver antennas, where the power decay law does not apply for estimating the signal power at a receiver. In this analysis we will assume, there are no two nodes in the network separated by a distance lesser than r_0.

bits, and l indicates the number of corrupted bits that can be tolerated while decoding a received packet. Accordingly, the PER, $p_p(r)$ is given by,

$$p_p(r) = 1 - \sum_{i=0}^{l} \binom{L}{i} \Big(p_b(r)\Big)^{i} \Big(1 - p_b(r)\Big)^{L-i} \tag{3}$$

Hence, the throughput offered by a r distance away forward direction neighbor is given by,

$$\eta(r) = 1 - p_p(r) \tag{4}$$

and the expected number of attempts $N_a(r)$ required for successful delivery of the packet to that node is:

$$N_a(r) = \frac{1}{1 - p_p(r)} \tag{5}$$

Let e_t be the energy consumed by the transmitter per packet transmission attempt, and e_r is the energy consumed at the receiver to receive a packet (which could be correct or corrupted). Then the energy that would be consumed per successful packet transmission to the r distance away forward direction neighbor at an intermediate hop would be:

$$E(r) = N_a(r)\big(e_t + e_r\big) \tag{6}$$

For the source and the destination end nodes the consumption would be $E = N_a(r) \cdot e_t$ and $E = N_a(r) \cdot e_r$, respectively.

The energy consumption per successful transmission per unit progress offered by the r distance away neighbor can be approximately given by:

$$E_c = \frac{E(r)}{r \cos\theta} \tag{7}$$

where $r\cos\theta$ is the distance progress toward the destination offered by the r distance away forward neighbor node, and θ is the angle of the neighbor node with respect to the straight line connecting the current transmitter and the destination, as shown in Fig. 2.

If there are K forward direction neighbors of the transmitter, with the k-th neighbor at a distance r_k $(k = 1, 2, \cdots\ K)$, then the chosen neighbor as the forwarding node is the one that offers $E_c^{(\text{min})} = \min_k \{E_c(r_k)\}$.

In GMFP, at each hop a forwarding neighbor is chosen based on the $E_c^{(\text{min})}$ criteria, until the data packet reaches the destination node. Since the sensor network applications are mostly not delay constrained, this state-less routing and forwarding approach is expected to satisfy the quality of service guarantee. Network performance in terms of network lifetime and end-to-end throughput is measured as stated in 2 and 3. It is yet to be studied how this protocol would fair with respect to other multihop forwarding approaches.

D. One-hop throughput computation

In general, the one-hop throughput offered for a r distance away selected forwarding node is given by (4) and (3), which gives the unconditional one-hop throughput as:

$$\eta = \sum_{r=r_0}^{R} \eta(r) \cdot \Pr[\boldsymbol{r} = r] = \int_{r_0}^{R} \eta(r) \cdot f(r) dr \tag{8}$$

where $f(r)$ is the pdf (probability density function) of the distance r of the chosen forwarding node, or equivalently the pdf of forward progress offered by the chosen forwarding node. The pdf would depend on the forwarding policy, and it can be complex to derive the expression particularly when multiple optimization criteria are involved, as in the case of GMFP.

While our current simulation-based performance evaluation does not need the pdf expression to compute the one-hop and hence end-to-end throughput performance, we show that an approximate expression can be obtained in case of greedy geographic LRD forwarding.

In contrast to GMFP, LRD forwarding chooses a next forwarding node solely based on proximity to the destination. The per-hop average Euclidean distance progress in LRD was derived in [7]. In view of the reference distance r_0 (within which range a forwarding node should not be located), the modified approximate pdf expression of the Euclidean distance progress $\mathbf{r_g}$ is given by (9), where $P(n)$ is the probability of n forward direction neighbors of a transmitter, which, by Poisson approximation of uniformly random node distribution is given by:

$$\Pr[\boldsymbol{n} = n] \triangleq P(n) = \frac{(\rho a_f)^n}{n!} e^{-\rho a_f} \tag{10}$$

ρ is the node density and $a_f = \pi R^2/2$, d is the current distance of the transmitter to the destination node, and R is the radious of circular communication (transmit/receive) range of the nodes.

In the following section, we show the relative performance results of GMFP and LRD forwarding via simulations.

IV. SIMULATION RESULTS AND DISCUSSION

Our preliminary performance evaluations have been carried out via discrete event simulations, where we have used GCC and Matlab. In a 700 × 700 square meter area we deployed sensor nodes uniformly randomly. The number of nodes were varied to achieve different network density. For our simulations we have taken standard values from the Chipcon RFIC datasheet [17]. Transmit power level was kept constant at 0 dBm, and the long-term average noise power was chosen -71 dB. Log-normal channel fading was simulated with a 4 dB standard deviation. BPSK modulation with NRZ signal was considered. Transmit energy consumption for one packet transmission, e_t was 0.208 mJ, and receiving energy consumption, e_r was 0.121 mJ. The initial energy of each node was taken as 100 mJ. Fixed packet size of $L = 320$ bits was taken and the number of recoverable bit errors was $l = 16$ bits. This values are equivalent to the existing standard coding mechanism. To avoid the boarder effects, only the nodes within inner $(700-R)\times(700-R)$ region was considered for selecting transmitter and receiver nodes, where R is the communication radius of a node. Sufficient simulation runs were conducted with varying seed values to have reasonably high confidence on the results.

Network performance results were taken by generating traffic between randomly chosen source-destination pairs. *Network lifetime* for different forwarding strategies were mea-

$$f_{\mathbf{rg}}(r) = \begin{cases} \sum_{n=0}^{\infty} 2nP(n) \left(\frac{2}{\pi(R^2-r_0^2)}\right)^n (d-r)\arccos\left(1+\frac{r^2-(R^2-r_0^2)}{2d(d-r)}\right) \left[\frac{1}{2}\sqrt{4(R^2-r_0^2)d^2 - \big((R^2-r_0^2)-r^2+2dr\big)^2} \right. & \\ \left. -(d-r)^2 \arccos\left(1+\frac{r^2-(R^2-r_0^2)}{2d(d-r)}\right) + (R^2-r_0^2)\arcsin\left(\frac{(R^2-r_0^2)-r^2+2dr}{2d\sqrt{R^2-r_0^2}}\right)\right]^{n-1}, & r_0 \le r \le R \\ 0, & \text{elsewhere.} \end{cases} \tag{9}$$

sured by the average maximum number of packets that can be successfully transmitted between randomly chosen source-destination pairs until a forward direction neighbor is found unavailable due to energy depleted nodes. *End-to-end throughput* was calculated as the number of successful end-to-end delivery with respect to the total number of end-to-end transmission attempts. *Average hop count* was measured as the average number of hops per successful delivery. To calculate *end-to-end energy consumption*, first 50 random source-destinations were chosen, and in each case 3 packets were to be successfully delivered to the destination. Total transmit and receive energy consumed in the process gave the measure of end-to-end energy consumption.

In Fig. 3 the end-to-end throughput results with respect to network density is shown. Since in GMFP a forwarding node is selected with link error condition in mind, it offers overall significantly higher throughput with respect to the LRD scheme.

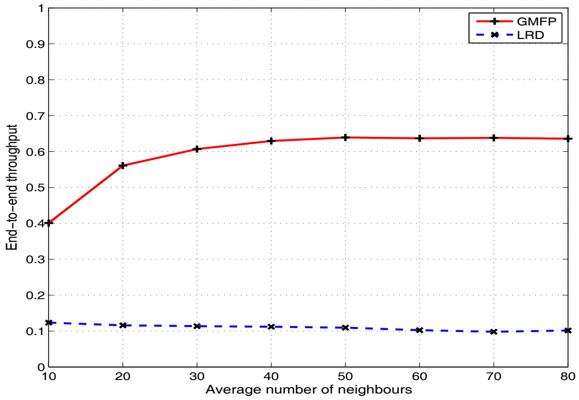

Fig. 3. End-to-end throughput versus average total number of neighbors ($2\rho a_f$). Communication radius $R = 60$ m.

Fig. 4 demonstrates the benefit of GMFP approach in terms of reducing the energy consumption along the active routes, where it shows that the LRD approach has significantly higher energy consumption. This has impact on the network lifetime, which is shown in Fig. 5.

Network lifetime performance is compared in Fig. 5, which again shows the benefit of minimum energy consumption forwarding, as it offers to extend the life significantly with respect to an approach with no energy awareness.

Finally, the average hop count measure has been compared in Fig. 6. It is apparent that GMFP approach requires quite larger number of hops to reach a destination, which is obvious because, as compared to the LRD forwarding approach, it tends to select nodes that are a little closer to the current transmitter. The network energy consumption and lifetime results shown earlier indicate that, even with a larger average hop count the network would be benefited by the GMFP protocol.

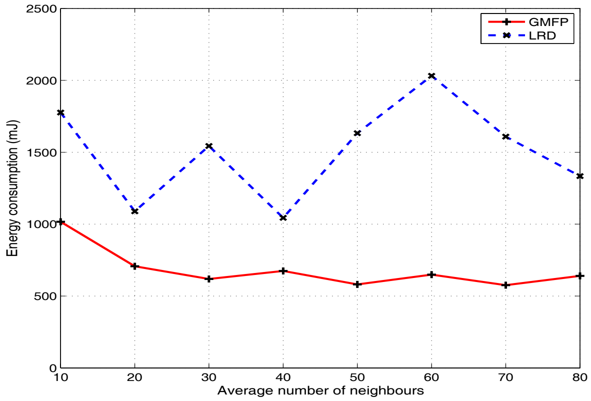

Fig. 4. End-to-end energy consumption, measured for first 150 successful packets, at different node density. $R = 60$ m.

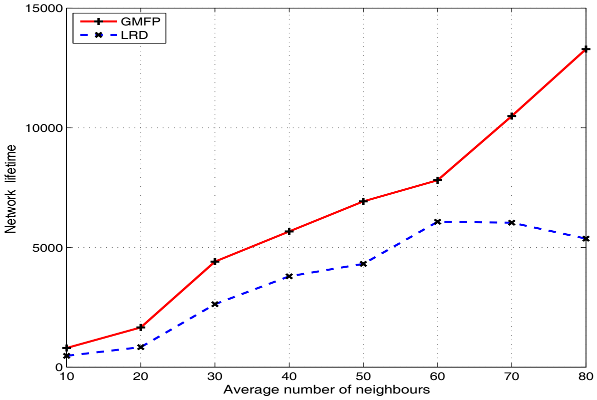

Fig. 5. Network lifetime (in terms of number of packets that can be successfully received before the network dies) at different node density. Communication radius $R = 60$ m.

To study the impact of even poorer link quality on GMFP and LRD performances, we have also conducted studies by varying the communication radius at a constant network density (with 3500 nodes deployed in the network) and at the same transmit signal power. The results are omitted here to avoid monotony. Overall, the performance results indicate that GMFP performs superior with respect to LRD forwarding.

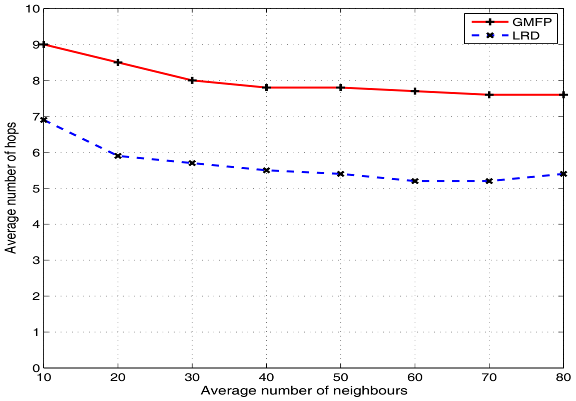

Fig. 6. Average hop count versus node density. $R = 60$ m.

V. CONCLUSION

In this paper we investigated a minimum energy consumption greedy forwarding algorithm for wireless sensor networks. Via analytic formulation and network simulations, we contrasted the performance of our proposed protocol with the conventional greedy geographic LRD forwarding technique. We showed that, by jointly considering the one-hop progress and transmit and receive energy consumption, network performance can be improved in terms of throughput as well as network lifetime, although the route length could be a little longer.

While the preliminary results presented here are compared with an energy consumption unaware protocol, we plan to carry out performance comparisons with the other competitive energy-aware protocols such as in [12]. We will also conduct further analytic studies to quantify the performance gain of our proposed approach.

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