ENERGY-EFFICIENT GEOGRAPHIC ROUTING IN ENVIRONMENTALLY POWERED WIRELESS SENSOR NETWORKS

Kai Zeng†, Wenjing Lou†, Kui Ren† and Patrick J. Moran‡

† Department of ECE, Worcester Polytechnic Institute, MA 01609
{kzeng, wjlou, kren}@wpi.edu
‡ AirSprite Technologies, Inc., Northborough, MA 01532
pmoran@airsprite.com

ABSTRACT

Current and potential applications of wireless sensor networks (WSNs) include military sensing, physical security, traffic surveillance, and environment monitoring, etc. Due to the fact that WSNs are composed of a large number of low-cost but energy constrained nodes, scalable and energy-efficient routing protocols are requisite for the WSN applications. In this paper, we study energy-efficient geographic routing protocols in environmentally powered WSNs, where the sensor nodes are capable of extracting energy from the environment. We propose a protocol, geographic energy-aware blacklisting routing with energy supply (GEBRES), which makes routing decision locally by jointly taking into account multiple factors – the realistic wireless channel condition, packets advancement to the destination, the energy availability on the node with environmental energy supply. Simulation results show that GEBRES is more energy efficient than the corresponding residual energy based protocols without considering the property of the energy changing (including recharging and consuming) rate. In particular, given the same energy and traffic models, GEBRES maintains higher minimum residual energy on nodes and achieves better load balancing in terms of having a smaller standard deviation of residual energy among nodes. GEBRES exhibits a little degradation on end-to-end delay, but does not compromise the end-to-end throughput performance.

I. INTRODUCTION

Current and potential applications of wireless sensor networks (WSNs) include military sensing, physical security, traffic surveillance, and environment monitoring, etc. WSNs are characterized by multihop lossy wireless links and severely resource constrained nodes. Among the resource constraints, energy is probably the most crucial one since sensor nodes are typically battery powered and the lifetime of the battery imposes a limitation on the operation hours of the sensor network. Unlike the microprocessor industry or the communication hardware industry, where computation capability or the line rate has been continuously improved (regularly doubled every 18 months), battery technology has been relatively unchanged for many years. Energy efficiency has been a critical concern in wireless sensor network protocol design. Researchers are investigating energy conservation at every layer in the traditional protocol stack, from the physical layer up to the network layer and application layer.

Among the energy consumption factors, communication has been identified as the major source of energy consumption and costs significantly more than computation [1]. Energy aware routing is one common approach at the network layer to the energy efficiency problem. In former energy aware routing protocols [2]–[6], sensors/nodes are assumed to be powered by batteries with limited/fixed capacity and then routing decisions are made based on the energy consumption by sending/receiving packets on the wireless links and/or residual energy on each node. The objective of those protocols is either minimizing the energy consumption or maximizing the network lifetime. A new observation related to energy aware routing is the availability of the so-called energy scavengers which are devices able to harvest small amount of energy from ambient sources such as light, heat or vibration [7]–[9]. Voigt, et al. [10] designed two solar-aware routing protocols that preferably route packets via solar powered nodes and showed that the routing protocols provide significant energy savings. All of these energy aware routing protocols do not take into account the availability of geographic information of nodes and the optimal path is calculated based on each node having global knowledge of the whole network, which is usually inapplicable in WSNs. Lin et al. [11] addressed the problem of power-aware routing with distributed energy replenishment for multihop wireless networks. A cost metric was proposed that considers node's battery residual energy, energy requirement for routing the packet along the path from source to destination, and energy replenishing rate. The distributed algorithm proposed in [11] needs to flood the whole network to get the optimal path. More comprehensive study is necessary to design efficient localized algorithm to achieve energy efficiency with environmental energy supply.

Another approach to energy efficiency at the network layer is geographic routing [12]–[22], which is predicated on the forwarding node being aware of the location information of itself, its neighbors and the destination. Geographic routing technique is particularly applicable in WSNs because almost all sensing and monitoring applications of sensor networks require sensors to be aware of their physical locations. One of the advantages of geographic routing is that the routing overhead is minimized – neither route establishment flooding nor per-destination state is required. Other properties such as scalability, statelessness and low maintenance overhead also make it an attractive technique especially in large-scale sensor networks. For pure geographic routing schemes [12], [13], packets are routed/forwarded locally and greedily to the one-hop neighbor that provides most positive advancement to the destination. Greedy forwarding can fail when a communication void happens, namely, when the current node is distance-wise closest to the destination than any of its neighbors, but has no direct connection to the destination to deliver the packets. A number of techniques have been proposed, such as face/perimeter routing, to complement and enhance greedy forwarding [14]–[16] in the face of communication voids. Several recent experimental studies on wireless ad-hoc and sensor networks [17], [18] have shown that wireless links can be highly unreliable and that this must be explicitly taken into account when considering higher-layer protocols. [19] showed the existence of a large "transitional region" where link quality has high variance. More recent works on geographic routing are aware of this more realistic lossy channel situation. Seada, et al. [20] articulated the distance–hop energy trade-off for geographic routing. They concluded that PRR ($Packet\ Reception\ Rate$) $\times$ $Distance$ is an optimal metric for making localized geographic routing decisions in lossy wireless networks with ARQ (Automatic Repeat reQuest) mechanisms. Lee, et al. [21] presented a more general framework called normalized advance (NADV) to minimize various types of link cost. The focus of these works is performance gain therefore none of them took into account the energy constraint on nodes. While some geographic routing protocol accounts for nodes' residual energy information such as GEAR (Geographic and Energy Aware Routing) [22], which uses energy aware and geography-based neighbor selection heuristics to route a packet towards the target region, it does not take into account the realistic wireless channel conditions and environmental energy supply.

In this paper, we carry out a more comprehensive study on energy efficient routing. We propose a protocol, geographic energy-aware blacklisting routing with energy supply (GEBRES), which makes routing decision locally by jointly taking into account multiple factors – the realistic wireless channel condition, packets advancement to the destination, the energy availability on the node with environmental energy supply. Simulation results show that our protocols are more energy efficient than the corresponding residual energy based protocols without considering the property of the energy renewal. In particular, given the same energy and traffic models, GEBRES maintains higher minimum residual energy on nodes and achieves better load balancing in terms of having a smaller standard deviation of residual energy among nodes. GEBRES exhibits a little degradation on end-to-end delay, but does not compromise the end-to-end throughput performance.

The rest of this paper is organized as follows. We explain system models in Section II, and propose GEBRES in Section III. We present and analyze our simulation results in Section IV. Section V presents our conclusions.

II. System Model

A. Observations and Assumptions

We assume that each network node is aware of its own and its one-hop neighbors' positions and the source of a message knows the position of the destination. This assumption is reasonable in a wireless sensor network due to its sensing and monitoring application nature – nodes need to be aware of their own locations when reporting their sensing data; the data are usually sent back to a known "sink" location. The distance between any two nodes, i and j, is the Euclidian distance between them, denoted as Dist(i,j).

Each network node is equipped with energy renewable batteries that can harvest energies from their working environment [7]–[9], [23].

A MAC protocol that allows retransmission is used, such as 802.11 [24]. The 802.11 ACK mechanism resends lost data frames, making all but the worst 802.11 links appear loss-free to the network layer.

Each node is informed with its own and its one-hop neighbors' battery residual energy level E_r and the short-term energy harvesting rate, μ_h, periodically. The residual energy in a battery can be estimated from its discharge function and measured voltage supplied [2]. Neighbor nodes exchange these information with each other by piggybacking them in the periodically broadcast "Hello" messages.

The network is dense enough so that no holes exist[1].

B. Energy Harvesting Model

Depending on the deployment conditions, such as whether or not directly exposed to sun light, the intensity of the sun light, the speed of air flow and so on, there is an uncertainty associated with environmental energy harvesting capability. We use a random process to model the energy harvesting rate of node i. We model the mean harvesting rate with a uniformly distributed random variable with mean μ_i, varying between Pi_{min} and Pi_{max}. The energy harvesting capability is not homogeneous at all nodes. In addition, energy collected by the scavengers can be stored in some energy reservoirs such as batteries, fuel cells, capacitors, etc. However there is a capacity limit of such an energy reservoir, beyond which environmentally available energy cannot be stored. We use constant E_b to denote such a battery capacity limit for each node.

C. Energy Consumption Model

In this paper, the cost for a node to send or receive a packet is modelled as a linear function similar to [25]. There is a fixed cost associated with channel acquisition and an incremental cost proportional to the size of the packet:

$$Cost = c \times S_{pkt} + b \tag{1}$$

Where c denotes the energy needed for sending or receiving one bit of data, S_{pkt} denotes the size of the data in bits and b is a constant. In this paper, we only consider the energy consumption when a node sends or receives data as most energy aware routing protocols do.

D. Link quality estimation

We denote the Frame Delivery Ratio (FDR)[2] from a node i to its neighbor j, FDR_{ij}. It is measured using "Hello" messages[3] which are broadcast periodically every τ time unit. Because the probes are broadcast, 802.11 does not acknowledge or retransmit them.

Exponentially Weighted Moving Average (EWMA) function [26] is used as the link quality estimation algorithm [4] which is often used in statistical process control applications. Two events will drive the updating of FDR_{ij} on node j: one is the periodical updating event set by the node, for example, every t_u seconds j will update FDR_{ij}; the other is the event that j receives a probe message, "Hello" packet, from i. This technique allows j to measure FDR_{ij} and i to measure FDR_{ji}. Each probe sent by a node i contains FDR measured by i from each of its neighbors N_i. Then each neighbor of i, N_i, gets the FDR to i whenever it receives a probe from i.

III. Geographic Energy-aware Blacklisting Routing with Energy Supply (GEBRES)

In our routing protocol, each node locally maintains the information of its one-hop neighbors such as the neighbor's location, residual energy, energy harvesting rate, energy consuming rate, and wireless link quality (in terms of FDR). We assume that node i is forwarding a packet M, whose destination is D. Node i tries to balance the geographical advancement per packet transmission and the energy availability on its neighbors N_i. This protocol is described as follows:

The node i blacklists, from its neighbors with positive $EADV(i, N_i, D)$ defined in Eq.(2) to the destination and $E(N_i)$ in Eq.(3) larger than $2 \cdot Cost$ in Eq.(1), a percentage φ of nodes that have the lowest $EADV(i, N_i, D)$ defined in Eq.(2). For example, if the blacklisting threshold is 25%, the node i considers only the 75% highest $EADV(i, N_i, D)$ neighbors of its neighbors that are closer to the destination than itself, and it forwards the packet to the neighbor having the most $E(N_i)$.

We eliminate the neighbors with $E(N_i)$ smaller than $2 \cdot Cost$, because when $E(N_i)$ is smaller than $2 \cdot Cost$ in Eq.(1), N_i does not have enough energy to receive and transmit a packet. In this paper, we assume there is no holes, so there is always at least one neighbor of node i satisfying $EADV(i, N_i, D) > 0$. We only consider the neighbors with $FDR_{iN_i} > 0.2$ and $FDR_{N_i i} > 0.2$ as the candidates of node i's next hop, since it will cause a lot of retransmissions if we choose neighbors having poor link quality from/to node i. Retransmissions will not only consume sender's energy but also increase the interference to other nodes.

$$\begin{aligned} EADV(i, N_i, D) = {} & (Dist(i, D) - Dist(N_i, D)) \\ & \cdot FDR_{iN_i} \cdot FDR_{N_i i} \end{aligned} \tag{2}$$

$$E(N_i) = \beta \cdot (\mu_{N_i} - \eta_{N_i}) \cdot (t_c - t_l) + E_r(N_i) \tag{3}$$

where β is a tunable weight. Recall that μ_{N_i} is the last received expected energy harvesting rate on node N_i by

[1]Communication void problem should be addressed in a separate paper.

[2]We use Frame Delivery Ratio instead of Packet Delivery Ratio here to differentiate the data delivery ratio observed from the MAC layer and the network layer. As mentioned before, due to the lossy links, some MAC protocols such as 802.11 retransmit lost data frames to guarantee high delivery ratio in network layer. That is, a successful packet transmission at network layer may cause a number of transmissions (including retransmissions) at the MAC layer.

[3]In our proposed protocols, "Hello" message is used for both exchanging neighbor nodes' information and probing link quality.

[4]Please refer to [26] for a complete description of the algorithm

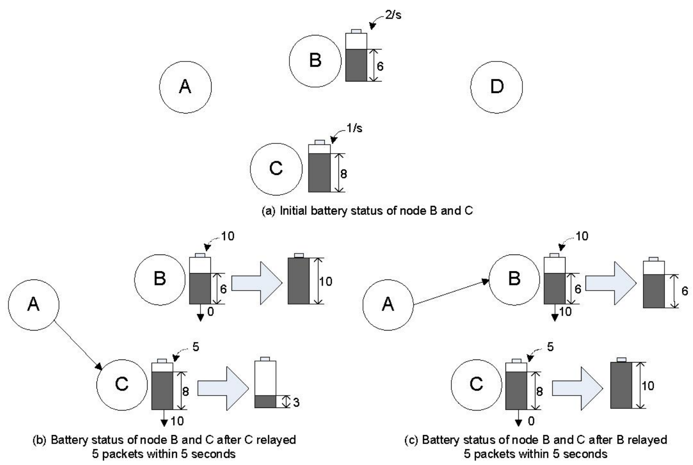

Fig. 1. Comparision of battery status of intermediate nodes between residual energy based protocol and GEBRES

node i. η_{N_i} is the last received expected energy consuming rate on node N_i by node i. t_c is the time when the node i is forwarding the packet. t_l is the last time when "Hello" message broadcast by N_i is heard by i, and μ_{N_i} and $E_r(N_i)$ are updated. η_{N_i} is updated every τ ("Hello" interval) at node N_i according to Eq.(4) when it broadcasts "Hello" message.

$$\eta_{N_i} = \frac{E_{c_\tau}(N_i)}{\tau} \tag{4}$$

where $E_{c_\tau}(N_i)$ is the energy consumed in the last interval τ.

The rationale to design GEBRES is as follows. In Eq.(2), the factor $FDR_{iN_i} \cdot FDR_{N_i i}$ is the inverse of the ETX (expected transmission count) defined in [17]. The physical meaning of Eq.(2) is the expected progress towards the destination per packet transmission. Eq.(3) is the energy availability represented by the linear combination of harvesting energy, consuming energy and the residual energy on the battery. In an environment where the energy source distribution is heterogeneous, GEBRES directs traffic to nodes with a faster energy renewal rate. Consider node i's neighbors having similar residual energy, energy consuming rate and $EADV$ to the destination. Among these neighbors, the one which can replenish their batteries at a higher rate will have larger $E(N_i)$ and will be selected as the next hop of node i. That is the reason why we choose the neighbor with the largest $E(N_i)$ instead of the largest residual energy $E_r(N_i)$ as the next hop.

For example, in Fig.1 (a), node A has two neighbors B and C, and A is going to send five packets to the destination D with one packet per second. B has a little larger $EADV$ to D than C, but the expected energy consumption per packet transmission from A to B and A to C are the same. Assume that B and C have the same battery capacity of 10 units of energy, and 6 and 8 units of residual energy respectively when A is doing the routing decision; their energy harvesting rates are 2 and 1 units of energy per second respectively; they consume the same energy, say 2 units, to receive a packet and forward the packet to their next hop. For energy aware routing only considering the residual energy information on nodes, A will send the packets to C because C has larger residual energy. As shown in Fig.1 (b), after relaying the five packets, C has residual energy of $8-10+5=3$ units since it consumes 10 units for relaying the packets meanwhile harvesting 4 units, and B has 10 units since it harvests 4 units. Although B can harvest 10 units in five seconds, the residual energy on it can not exceed the battery capacity, 10 units. For GEBRES, $E(B) = 6 + 2 * 5 = 16$ and $E(C) = 8 + 1 * 5 = 13$, then $E(B) > E(C)$, so B will be selected as the next hop of A. As shown in Fig.1 (c), after relaying the five packets, B has residual energy of 6 units since it consumes 10 units for relaying packets meanwhile harvesting the same amount of $2 * 5 = 10$ units, and C has residual energy of 10 units since it harvests 2 units. So the minimum residual energy on nodes using GEBRES is larger than that using residual energy based protocol, and GEBRES achieves better load balancing than corresponding residual energy based protocol in terms of having smaller standard deviation of residual energy (2 units) than that (3.5 units) of residual energy based protocol. We will give the formal definition of these metrics in section IV-B.

IV. Performance Evaluation

A. Simulation Setup

All the simulations are implemented within the GloMoSim library [27], which is a scalable simulation environment for wireless network systems. The simulated sensor network has $N = 196$ stationary nodes uniformly distributed in a $d \times d\ m^2$ square region, with nodes having identical fixed transmission power. We use $d = 250, 210, 180, 160$ to achieve various node densities in terms of average neighborhood sizes of $10, 15, 20, 25$. For GEBRES, β in Eq. (3) is set to be 1 when $d = 250$ and 210, and 5 when $d = 180$ and 160. The blacklisting percentage φ is 0.5. The "Hello" interval τ is set to be $60s$. To simulate a randomly lossy channel, we assume Ground Reflection (Two-Ray) path loss model and Ricean fading model [28] for signal propagation. The packet reception decision is based on the SNR threshold. When the SNR is larger than a defined threshold, the signal is received without error. Otherwise the packet is dropped. We set proper parameters to make the maximum transmission range as $35m$. IEEE 802.11 [24] is used as the MAC layer protocol. Each

	High	Low
Min (mw)	0.1	0.01
Max (mw)	0.5	0.05

TABLE I

LEVEL OF ENERGY HARVESTING RATE

node was initialized with a fixed amount of energy/battery reserve (E_b = 5000 mJ) before network deployment. The energy consumption model is described in section II-C, where $c = 0.24\mu J/bit$ for sending and receiving packets and $b = 450\mu J$ for sending packets and $b = 260\mu J$ for receiving packets. The energy harvesting model is described in section II-B. Two nodal energy harvesting rates are assumed in Table I. Each node's harvesting rate is randomly chosen to be one of the two levels and is fixed on the level in one simulation run. We apply peer-to-peer application traffic, which consists of fifteen randomly chosen communication pairs in the simulation area. The sources are CBR (constant bit rate) with one packet per second and each packet being 512 bytes long. Each point in the plotted results represents an average of ten simulation runs with different seeds. We compare GEBRES with its two extreme cases: one is denoted as "Residual only", where each packet is locally sent to the neighbor with maximum residual energy among all the neighbors, which is equivalent to set both β and φ as 0 in GEBRES; the other is the corresponding residual energy based blacklisting protocol, denoted as "Residual-based-blacklisting", where φ is the same as 0.5 as in GEBRES, while β in Eq. (3) is set to be 0.

B. Evaluation Metrics

We define the following two metrics to show the energy efficiency performance of the routing protocols.

- *Minimum residual energy (Min_r)*: This metric calculates the minimum residual energy at the end of simulation for all the sensor nodes. The higher the value is, the better the performance is.
- *Standard deviation of residual energy (σ_r)*: It is calculated as in Eq. (5), which measures the standard deviation of the residual energy of all nodes. This quantity indicates how well the traffic load/energy consumption is distributed among nodes. The smaller the value is, the better the capability the routing protocol has in balancing the energy consumption.

$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_r(i) - \mu_r)^2} \qquad (5)$$

The following performance metrics are also measured to evaluate the Quality of Service (QoS) provided by the routing protocols.

- *Normalized end-to-end throughput:* This metric is measured in bit-meters per second (bmps) as in [29]. It is calculated as in Eq. (6),

$$T(S, D) = \frac{N_{delivered} \cdot S_{pkt} \cdot Dist(S, D)}{t_{session}} \qquad (6)$$

  where $T(S, D)$ denotes the normalized throughput from source node S to destination node D, $N_{delivered}$ denotes the number of packets delivered from S to D in the communication session, S_{pkt} denotes the packet size in bits, $Dist(S, D)$ denotes the Euclidean distance between S and D in meters, and $t_{session}$ denotes the communication session duration from S to D in seconds. We account for the distance factor, because the throughput is indeed relative to the distance between the communication pair due to the lossy property of multi-hop wireless links in WSNs.
- *Normalized end-to-end delay:* It is measured as the per packet delay from S to D over $Dist(S, D)$ in second per packet-meter (sppm), as the delay is also proportional to the distance between the communication pair.

C. Simulation results and analysis

Fig. 2 and 3 show that under randomly distributed peer-to-peer application traffic, GEBRES is more energy efficient than the "Residual-based-blacklisting" protocol in terms of having higher minimum residual energy and smaller standard deviation of residual energy. "Residual only" protocol has the smallest standard deviation of residual energy, but has the lowest minimum residual energy on nodes. From Fig. 4 and 5, we observe that "Residual only" protocol has the worst QoS performance in terms of having the lowest end-to-end throughput and largest end-to-end delay. Comparing to "Residual-based-blacklisting" protocol, GEBRES has almost the same throughput and a little larger delay.

These results can be explained as following. GEBRES takes into account the energy changing rate (including the environmental energy harvesting rate and the energy consuming rate) as well as the residual energy on nodes, so it has more accurate energy availability estimation than the other two protocols and is most energy efficient. GEBRES delivers packets along wireless links with almost the same $EADV$ as the "Residual-based-blacklisting" protocol. Therefore, the QoS performance of GEBRES is almost the same as the "Residual-based-blacklisting" protocol. For "Residual only" protocol, as the neighbors with small $EADV$ are not blacklisted, packets being sent to the neighbor with the highest residual energy without considering

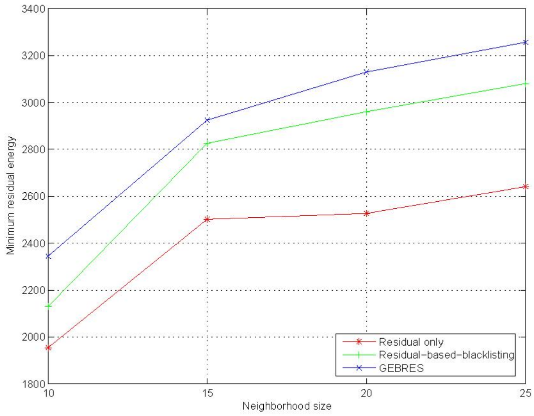

Fig. 2. Minimum residual energy on nodes at the end of the simulation under randomly distributed peer-to-peer application traffic

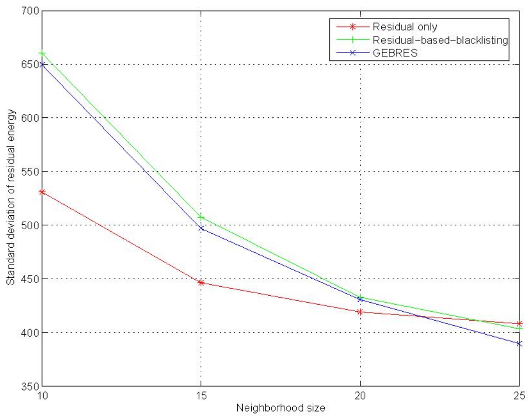

Fig. 3. Standard deviation of residual energy on nodes at the end of the simulation under randomly distributed peer-to-peer application traffic

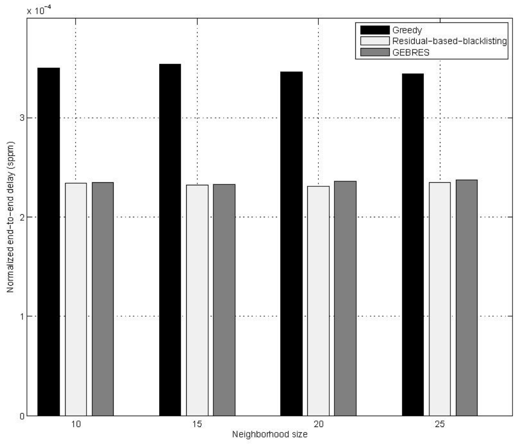

Fig. 4. Normalized end-to-end delay under randomly distributed peer-to-peer application traffic

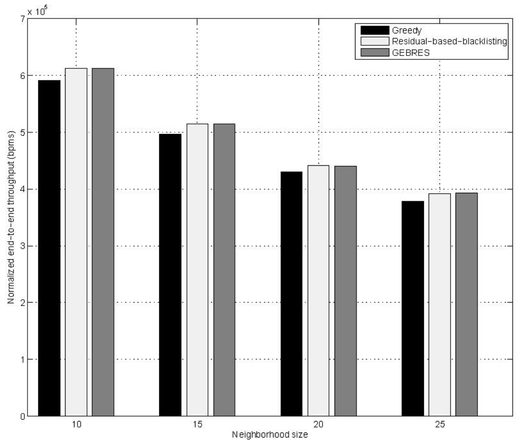

Fig. 5. Normalized end-to-end throughput under randomly distributed peer-to-peer application traffic

the $EADV$ results in that some packets are delivered on the wireless links with smaller $EADV$ than the other two protocols. Therefore, more hops are needed to deliver a packet from the source to the destination for the "Residual only" protocol than the other two protocols, then "Residual only" protocol costs the most transmissions and receptions to deliver a packet. As the energy consumption for each transmission and reception is fixed for each packet, the "Residual only" protocol consumes the most energy and has the lowest minimum residual energy. "Residual only" protocol has the worst QoS performance in terms of having the largest delay and smallest throughput because a number of packets are delivered on some lossy links with low FDR and/or small advancement.

Another observation from Fig. 2 and 3 is that the more densely the nodes are deployed the more minimum energy remained on nodes and the smaller is the standard deviation. Because we fix the node transmission power, when the nodes are closer to each other, the hop counts needed to deliver the packet from the source to the destination become smaller, then the required energy for delivering one packet from the source to the destination is reduced. Furthermore, when network is denser, the number of paths between the communication pairs increases, each node has more choices of the next hop to distribute traffic load, and the result is the decreased energy consumption variance among all the nodes.

In Fig. 4, we can see that the delay performance is not changed much with network density, as we already normalize the delay by dividing it by distance. In Fig. 5, throughput is smaller when nodes are closer (denser) since the throughput is normalized by multiplying the source-destination distance.

V. Conclusion and Future Work

In this paper, we study energy-efficient geographic routing protocols in environmentally powered WSNs, where the sensor nodes are capable of extracting energy from the environment. We propose a protocol, geographic energy-aware blacklisting routing with energy supply (GEBRES), which makes routing decision locally by jointly taking into account multiple factors – the realistic wireless channel condition, packets advancement to the destination, the energy availability on the node with environmental energy supply. Simulation results show that our protocol is more energy efficient than the corresponding residual energy based protocols without considering the property of the energy changing (including recharging and consuming) rate. In particular, given the same energy and traffic models, GEBRES maintains higher minimum residual energy on nodes and achieves better load balancing in terms of having a smaller standard deviation of residual energy among nodes. GEBRES exhibits a little degradation on end-to-end delay, but does not compromise the end-to-end throughput performance. Our future work is the theoretical analysis of the protocols and a more comprehensive simulation study which will be focusing on the understanding and optimization of the tunable parameters under various practical situations.

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