Adaptive Opportunistic Routing Protocol for Energy Harvesting Wireless Sensor Networks

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***Abstract*—Using energy harvesting WSNs (EH-WSNs) are attractive as they can be solely powered by ambient energy sources. Multi-hop routing is important to achieve wide coverage as the transmission range of each node is limited. In this paper, we propose an adaptive opportunistic routing (AOR) protocol for multi-hop EH-WSNs that achieves high throughput using a regioning scheme that adapts to network conditions and energy availability. We evaluate AOR using extensive simulations incorporating experimental results from the characterization of different types of energy harvesters. The results show that AOR increases throughput in both monitoring and event-driven WSNs with different node densities and energy harvesting rates compared to traditional opportunistic routing protocols and other non-opportunistic routing protocols. We have also implemented AOR on a testbed of 20 energy harvesting sensor nodes and results show that AOR works well in EH-WSNs.**

I. INTRODUCTION

Advances in energy harvesting technologies [1] have made it possible for sensor nodes to rely solely on energy harvesting devices for power. Each energy harvesting wireless sensor node typically comprises one or more energy harvesters, an energy storage device (e.g., supercapacitor) to store the harvested energy, a sensor for measurement, a micro-controller for processing and a transceiver for communications. In this paper, we propose AOR (Adaptive Opportunistic Routing), which is a multi-hop opportunistic routing protocol that can achieve high throughput, fairness and wide coverage in EH-WSNs. AOR is also scalable to high node densities and energy harvesting rates. The rest of this paper is organized as follows: In Section II, we review some work on routing protocols in EH-WSNs. Then, we describe AOR, an opportunistic routing protocol designed for multi-hop EH-WSNs in Section III. The performance of AOR under different scenarios is illustrated in Section IV. We conclude the paper in Section V.

II. RELATED WORK

In EH-WSNs, maximizing the network's workload is the main consideration since energy can be replenished, therefore a routing algorithm that takes into consideration energy harvesting nodes is required. In [2], the authors model the network as a flow network and solve the maxflow problem to maximize throughput. In [3], the energy replenishment rate is incorporated into the cost metric when computing routes. In [4], a routing metric can be derived to maximize network lifetime if both batteries and supercapacitors are used. In [5], directed diffusion is modified to incorporate information on whether a node is running on solar power or on battery power.

Another method to route packets in sensor networks is through the use of clusters (e.g., LEACH [6]). In EH-WSNs, nodes with energy harvesters are chosen as cluster heads since the energy can be replenished. sLEACH [7], which is an extension to LEACH, chooses cluster heads probabilistically and energy harvesting sensor nodes are assigned higher probabilities compared to battery-powered nodes.

In [8], geographic routing is used with routing decisions that takes into consideration energy harvesting nodes to improve performance. In [9], we have shown that *G*eographic *R*outing with *D*uplicate *D*etection (GR-DD), which is a broadcast-based geographic routing protocol, performs well in EH-WSNs under different network topologies and deployment scenarios. It performs duplicate detection to reduce interference and packet collisions. An unicast geographic routing protocol can also be used with a Wakeup Schedule Function (WSF) [10] which allows each node to wake up asynchronously without coordination with other nodes. With a (u, w, v) block design, each node will harvest enough energy to be active for w slots over a block of u slots and any two blocks will have v common slots.

Opportunistic Routing (OR) is a scheme that takes advantage of the broadcast nature of the wireless medium to improve link reliability and system throughput. It comprises (i) *forwarding candidates selection*, which determines the set of forwarding nodes and (ii) *relay priority assignment*, which determines the transmission priority among the set of forwarding candidates. We illustrate OR using the scenario in Fig. 1 where there is a sender, 12 nodes labeled from 1 to 12 and a sink. In the forwarding candidates selection phase, nodes 1 to 5 will drop the received broadcast packet from the sender since they are further away from the sink than the sender is. Next, we need to assign the transmission priorities for the forwarding candidates, nodes 6 to 12. Ideally, if the sink receives the data packet directly from the sender, all the forwarding candidates should not rebroadcast the received packet. Otherwise, the forwarding candidate nearest to the sink that receives the data packet should forward it first. For example, if nodes 7, 9, and 11 receive the data packet, node 11 should forward the data packet first. This concept is particularly suited for EH-WSNs as nodes do not know when and which other node(s) are awake at any time. Hence, we first propose EHOR [11] for a linear EH-WSN. AOR extends EHOR for a 2D EH-WSN, thus catering to a wider range of application and deployment topologies.

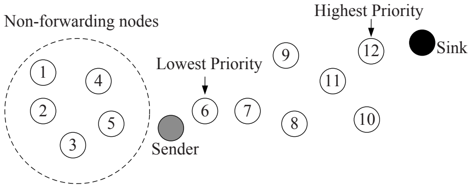


Fig. 1. Example of Opportunistic Routing

III. ADAPTIVE OPPORTUNISTIC ROUTING (AOR) PROTOCOL DESIGN

A. *Definitions and Assumptions*

We assume that n energy harvesting nodes and a sink node are randomly deployed over an area measuring l_x by l_y. The sink is a data collection point which is connected to the power mains, and is therefore always active. The transmission range of the node, d_{tr}, is defined as the maximum distance where the packet delivery ratio (PDR) is above the threshold Th. The value of d_{tr} can be determined from experiments or calculated using a suitable propagation model. The location information of each node can be pre-programmed into the nodes or obtained using a localization algorithm.

The n nodes comprise relay and source nodes: relay nodes only forward data packets towards the sink; source nodes are similar to relay nodes, except that they generate *new* data packets (each with a unique ID) and transmit them when there are no packets to relay. The source nodes will transmit new data packets whenever they have enough harvested energy, therefore the sending rate of new data packets depend on their energy harvesting rates.

Even with the state-of-the-art energy harvesters, the rate of energy harvesting may be lower than typical power consumption levels. As such, the node can be in one of two states: (i) *charging* - in this state, the node is inactive and harvested energy is cumulatively stored; (ii) *active* - in this state, there is sufficient stored energy to listen, receive and transmit data packets. We consider a simple energy management scheme (Fig. 2) whereby the node switches to active state whenever the stored energy reaches E_m, which is the energy required to remain active for a period of t_a, and switches back to charging state when the stored energy is depleted.

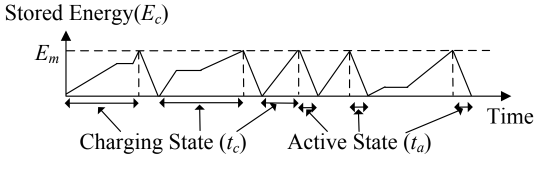


Fig. 2. Simple Energy Management Scheme

B. *Regioning in AOR*

The basic idea of AOR is as follows: (i) for each sender, the forwarding region is partitioned into k regions; (ii) upon receiving the data packet from the sender, each node in region j, $1 \leq j \leq k$, will forward it in the j^{th} time slot provided the node has enough energy and that the packet may not have been successfully received downstream.

The first issue in AOR is to determine the best forwarding candidates to forward the data packets while minimizing coordination overheads and duplicate transmissions. Since we cannot determine the exact identities of nodes that are awake at any time, AOR divides the possible set of forwarding candidates into k forwarding regions, as illustrated in Fig. 3 for k = 5. If the sink is outside the transmission range of the sender, there would be an additional region which consists of nodes outside the transmission range of the sender.

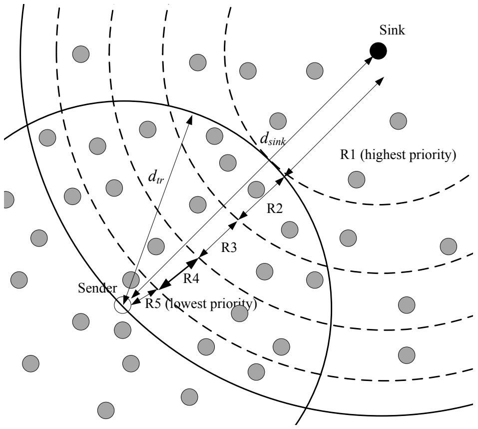


Fig. 3. Illustration of region concept in AOR (k=5)

1) Determination of k: For a sender node, we let A be the area of the forwarding region that is within its transmission range, as illustrated in Fig. 4. Since there are n sensor nodes, the average number of relay nodes within the forwarding region for each node, n_1, is $\lfloor \frac{A}{l_x l_y} n \rfloor$. To reduce the probability of concurrent transmissions which will lead to a collision, we want an average of one awake node in each region. If we let p_{rx} be the probability that a node can receive a data packet from a sender, then the value of k is

$$k = \lceil n_1 p_{rx} \rceil + 1. \quad (1)$$

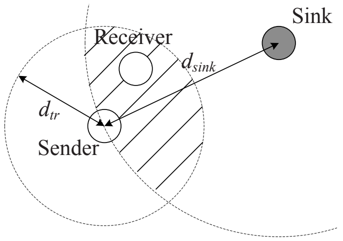


Fig. 4. Illustration of the forwarding region A (shaded for the sender)

Since most of the active time are in the receive state, p_{rx} can be approximated using $p_{rx} = \frac{\lambda}{P_{rx}}$, where λ is the average energy harvesting rate. We compute A by considering the intersection area between two circles shown in Fig. 5 where d_{sink} is the distance from the sender to the sink. In general, for two circles of radius r and R with inter-circle distance of d_c, the area of intersection $A_i(r, R, d_c)$ [12] is

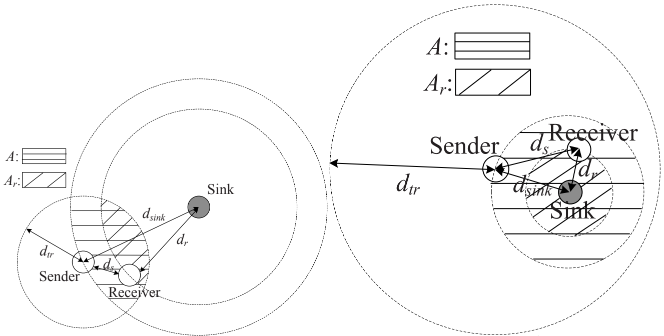
$$A_i(r, R, d_c) = r^2 \cos^{-1} \frac{{d_c}^2 + r^2 - R^2}{2 d_c r} + R^2 \cos^{-1} \frac{{d_c}^2 + R^2 - r^2}{2 d_c R} - \frac{\sqrt{(-d_c + r + R)(d_c + r - R)(d_c - r + R)(d_c + R + r)}}{2} \quad (2)$$

The value of A can then be computed using Algorithm 1.

2) Determination of Region ID: For a relay node r that is at a distance of d_s from the sender, its region ID j is

$$j = \begin{cases} 1, & d_s > d_{tr}; \\ 1 + \lceil \frac{A_r}{A} * (k-1) \rceil, & d_s \le d_{tr}, \end{cases} \quad (3)$$

where A_r is the area within A in which all the nodes are nearer to the sink than receiver r, as illustrated in Fig. 5. As with A, A_r can be computed based on the intersection of two circles, and its computation is given in Algorithm 1.



(a) $d_{sink} > \frac{1}{2} d_{tr}$ (b) $d_{sink} \le \frac{1}{2} d_{tr}$

Fig. 5. Illustration of areas A and A_r

Algorithm 1 Computation of A and A_r

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if $d_{sink} > \frac{1}{2} d_{tr}$ then
    $A = A_i(d_{tr}, d_{sink}, d_{sink})$
    if $d_r \ge d_{tr} - d_{sink}$ then
        $A_r = A_i(d_{tr}, d_r, d_{sink})$
    else
        $A_r = \pi {d_r}^2$
    end if
else
    $A = \pi {d_{sink}}^2$
    $A_r = \pi {d_r}^2$
end if
```

Once a packet has been received by the active nodes in the forwarding regions, AOR has to determine the transmission priority. Since there are k regions, k time slots are assigned for the nodes to transmit. A node in the j^{th} region will transmit in the j^{th} time slot after arrival of the packet as long as the node has enough energy and the packet has not been relayed by higher-priority nodes.

Finally, we need to compute E_m. We let the data packet size (including all headers) be s_d bytes and the transmission rate of the sensor node be α bps. The time taken to transmit one data packet is $t_{tx} = 8 s_d / \alpha$. The duration of each time slot can be computed using $t_{slot} = t_{prop} + t_{ta} + t_{tx}$, where t_{prop} is the maximum propagation delay and t_{ta} is the hardware turnaround time from receive to transmit state. The maximum time in receive mode, denoted by t_{rmax}, must be greater than the number of time slots, i.e., $t_{rmax} > k t_{slot}$. In this paper, we let $t_{rmax} = (k+1) t_{slot}$. We denote the maximum energy required in the receive state by E_{rxmax}, the energy required to transmit a data packet by E_{tx}, the energy required to change from receive state to transmit state by E_{ta} and the minimum energy for the node to become active by E_m. We let the receive and transmit power of the sensor be P_{rx} and P_{tx} respectively. Therefore, we have $E_{rxmax} = P_{rx} t_{rmax}$, $E_{tx} = P_{tx} t_{tx}$, $E_{ta} = \frac{P_{rx} + P_{tx}}{2} t_{ta}$ and $E_m = E_{rxmax} + E_{ta} + E_{tx}$.

C. Energy Considerations in AOR

In opportunistic routing, nodes nearer the sink are favored without considering the energy availability of a node. In EH-WSNs, a node that is scheduled to transmit in a particular slot may be unable to do so due to energy constraints. For example, in the scenario as shown in Fig. 3, nodes in R1 have the lowest probability of receiving the data packet since they are furthest away from the sender but they have the highest probability of forwarding the data packet since they can transmit immediately after receiving the data packet. Nodes in R5 have the highest probability of receiving the data packet since they are nearest the sender but they have the lowest probability of sending the data packet since they have to wait for 4 time slots to determine whether nodes in R1-4 have relayed the packet or not. At the end of this waiting time, the node may not have enough energy to forward the data packet.

This observation means AOR can be improved by adjusting the transmission priority based on the available energy in the node for the current active period, in addition to its distance from the sink. Nodes that are nearer (further from) the sink but have more (less) remaining energy would have their priority reduced (increased). Accordingly, if the remaining energy of the node at the end of the packet reception from the sender is E_{re} for the current active period, then the j^{th} time slot in which it is scheduled to transmit in is

$$j = \lceil \beta * j_d + (1 - \beta) * j_e \rceil \quad (4)$$

where

$$j_d = \begin{cases} 1, & d_s > d_{tr}; \\ 1 + \frac{A_r}{A} * (k-1), & d_s \le d_{tr}, \end{cases}$$

and

$$j_e = \begin{cases} 1, & d_s > d_{tr}; \\ \frac{E_{re} - E_{ta} - E_{tx}}{t_{slot} P_{rx}}, & d_s \le d_{tr}. \end{cases}$$

The factor, β, $0 \le \beta \le 1$, weighs the forwarding priority of a node between its stored energy and quality of the direct link (based on distance) with the sink. With β = 0 (1), nodes with lower remaining energy (nearer the sink) will be assigned higher forwarding priority.

IV. PERFORMANCE EVALUATION

We use the Qualnet [13] network simulator to evaluate AOR in an 500m × 500m EH-WSN. Each data point is derived from the average of 10 simulation runs of duration 100s each using different seeds and node deployments. We have incorporated the specifications of the TI EH-WSN node [14] into our simulations: the transmission rate of the node is 250 kbps, the hardware turnaround time is 0.192 ms and the receive and transmit powers are 72.6 mW and 83.7 mW respectively. For AOR, we choose $Th = 10\%$ to exploit the benefits of opportunistic routing. Based on the radio characterization results in [15], we set the transmission range, d_{tr} to 70m and model the radio propagation using a lognormal shadowing model and a Ricean fading model. The TI sensor nodes allow packet sizes larger than those using TinyOS, so the size of each data packet (s_d) is set to 100 bytes to minimize overheads.

Throughput is defined as the rate of *unique* packets received by the sink. We use Jain's fairness metric for multi-source scenarios. It is defined as $F = \frac{(\sum_{i=1}^{n_s} G_i)^2}{n_s(\sum_{i=1}^{n_s} G_i^2)}$, where G_i is the throughput of the i^{th} sensor node. F is bounded between 0 and 1. If the sink receives the same amount of data from all the source sensor nodes, F is 1. If the sink receives data from only one node, then $F \to 0$ as $n \to \infty$.

We consider both event-driven and active monitoring sensor network applications. In event-driven WSNs, data is only transmitted when an event or anomaly is detected. In active monitoring WSNs, sensed data is periodically sent to the sink for analysis or collection. There are typically more source nodes in active monitoring WSNs than event-driven WSNs.

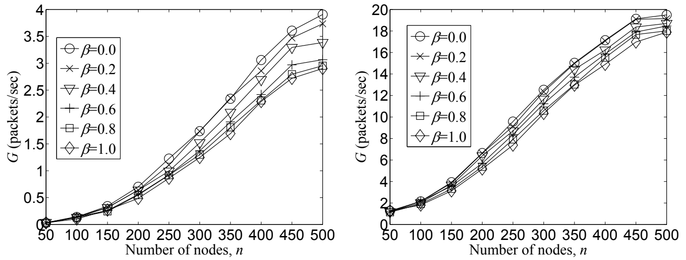
A. Impact of β in event-driven WSNs

As β is a key design parameter in AOR, we will first determine the impact of different values of β on network performance. For event-driven EH-WSNs, the source nodes are chosen so that they are furthest away from the sink to demonstrate multi-hop communications. We consider the scenario with energy harvesting rate (λ) of 10mW and vary the total number of nodes from 50 to 500 with 1 or 10 source nodes. Since the energy harvesting rate is much lower than the power consumption level of the node, the node cannot be active at all times and the unpredictability in the energy harvesting process results in different charging times for each charge cycle. The charging time distribution is based on empirical measurements using the TI nodes given in [16].

The performance results are illustrated in Fig. 6 for different values of β from 0 to 1. The throughput is maximized by setting β to 0 as this increases the probability of a relay node forwarding a data packet by considering energy availability. This results in some shorter links being used and therefore increases the total number of transmissions needed.

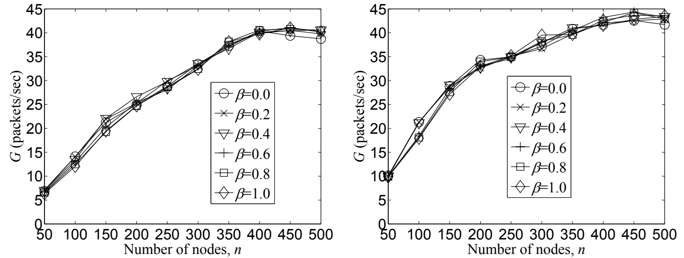
B. Impact of β in active monitoring WSNs

Next, we consider an active monitoring EH-WSN with the number of source nodes, which are randomly chosen, set at 10% and 20% of the total number of nodes. As illustrated in Fig. 7, β does not have significant impact on throughput unlike event-driven EH-WSNs, . This is because the number of source nodes is comparatively higher in this scenario, therefore any increase in throughput due to more transmissions by relay nodes is offset by collision losses and higher interference from the increased traffic. By giving long-distance links higher priority ($\beta > 0$), throughput will increase in some scenarios as the number of transmissions needed per packet to reach the sink is reduced, thereby reducing MAC contention.



(a) Throughput (n_s=1) (b) Throughput (n_s=10)

Fig. 6. Performance results for an event-driven WSN (n=50 to 500,λ=10mW)



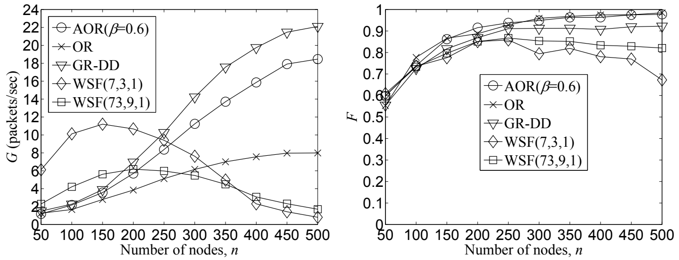
(a) Throughput ($n_s = n/10$) (b) Throughput ($n_s = n/5$)

Fig. 7. Performance results for an active monitoring WSN (n=50 to 500,λ=10mW)

C. Comparison of AOR with other routing protocols

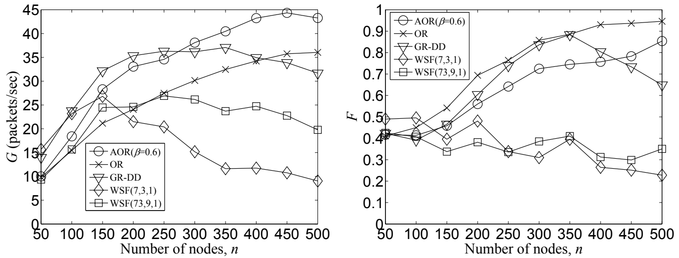
Next, we compare AOR with other routing protocols for EH-WSNs which include basic opportunistic routing (OR) (i.e., AOR without regioning and energy considerations), a broadcast-based geographic routing protocol (GR-DD) for EH-WSN [9] and unicast routing using an asynchronous wakeup schedule protocol (WSF) [10] with block designs of (7,3,1) and (73,9,1). We use β of 0.6 for AOR since it achieves good performance for both event-driven and monitoring WSNs. The results are illustrated in Fig. 8 for both event-driven and active monitoring EH-WSNs. While AOR and GR-DD can scale to large number of nodes, the WSF scheme does not work well for high density node deployments due to excessive MAC collisions during the beaconing and data transmission process. AOR outperforms OR due to the regioning scheme and energy availability considerations. AOR also achieve high fairness as it can receive data packets from all the source nodes.

To determine the scalability of AOR, we increase the energy harvesting rates and node densities. As illustrated in Fig. 9, even at a very high energy harvesting rates of 100 mW or node density of 1,000 nodes, the throughput of AOR is maintained or is only degraded gradually compared to GR-DD.



(a) Throughput for 10 source nodes ($n_s = 10$)

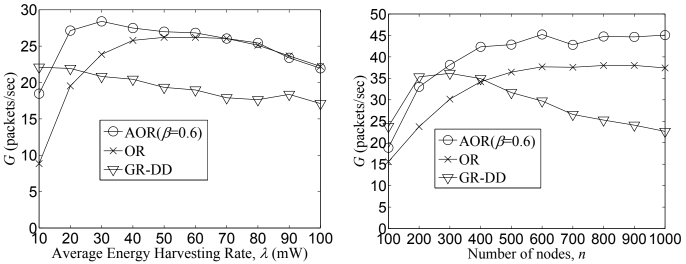
(b) Fairness ($n_s = 10$)



(c) Throughput for 20% source nodes ($n_s = n/5$)

(d) Fairness ($n_s = n/5$)

Fig. 8. Performance comparison between different routing protocols for event-driven and active monitoring EH-WSNs (n=50 to 500,λ=10mW)



(a) Throughput for 10 source nodes ($n_s = n/10$)

(b) Throughput for 20% source nodes ($n_s = n/10$)

Fig. 9. Scalability of AOR

D. Implementation

We have implemented AOR on an indoor testbed comprising 10 to 20 TI EH-WSNs nodes [14] with one source node placed about 2 to 3 hops away from the sink using energy harvesting rate of 20 mW. The experiments are repeated 5 times for each data point using different node deployments with each experiment lasting 5 minutes. Fig. 10 shows that the experimental results (with 95% confidence intervals) are reasonably close to the simulation results, which confirms that AOR improves throughput over traditional OR protocols.

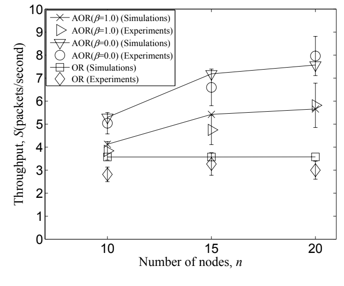


Fig. 10. Experimental evaluation of AOR in multi-hop scenarios

V. CONCLUSION

In this paper, we have designed an opportunistic routing protocol (AOR) for energy harvesting wireless sensor networks. We use a regioning approach to group nodes together and consider energy availability in each node in addition to its distance from the sink when determining its transmission priority. We evaluate AOR using extensive simulations and the results show that assigning transmission priorities to the nodes according to distance and available energy is important to achieve good network performance. We conclude that giving higher priority to energy availability (i.e., lower β values) work well when the traffic is light with few source nodes but giving higher priority to distance (i.e., higher β values) works better in the presence of higher traffic with higher number of source nodes. When compared to other non-OR routing protocols, AOR achieves high throughput, fairness and scalability.

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