Opportunistic Routing with Adaptive Harvesting-aware Duty Cycling in Energy Harvesting WSN

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***Abstract*—With recent advances, the trend has shifted from battery-powered wireless sensor networks towards ones powered by ambient energy harvesters (WSN-HEAP). In such networks, operability of the node is dependent on the harvesting rate which is usually stochastic in nature. Therefore, it is necessary to devise routing protocols with energy management capabilities that consider variations in the availability of the environmental energy. In this paper, we design OR-AHaD, an Opportunistic Routing algorithm with Adaptive Harvesting-aware Duty Cycling. In the proposed algorithm, candidates are primarily prioritized by applying geographical zoning and later coordinated in a timer-based fashion by exchanging coordination messages. An energy management model is presented that uses the estimated harvesting rate in the near future to adjust the duty cycle of each node adaptively. Simulation results show that OR-AHaD exploits the available energy resources in an efficient way and increases goodput in comparison to other opportunistic routing protocols for WSN-HEAP.**

I. INTRODUCTION

Energy limitation is a major challenge which has been addressed many times in the context of wireless sensor networks. Traditionally sensor nodes were equipped with batteries and therefore their lifetime was bounded to their battery life. However, recently the trend has headed towards wireless sensor networks which are powered by ambient energy harvesters with the advantages of being cheaper, more environmentally friendly and most importantly capable of being recharged many times [1]. In this case, the operability of the node is dependent on the harvesting rate which is currently much less than the average energy consumption of the node and also usually stochastic in nature [2]. As a result, it is important to develop novel routing protocols that consider the variations in the available environmental energy.

In literature, a number of energy-aware routing solutions have been proposed for WSN-HEAP. The authors of [3] described energy sustainability as achieving maximum workload rather than increasing the lifetime which was tailored to battery-powered sensors. In [4], a mathematical framework was associated with analytical strategies to parameterize the real characteristics of the environmental energy and evaluate the benefits of energy-aware routing in the presence of renewable energy sources. While few existing studies explicitly take into account the time varying environmental energy, many of them still focus on the residual energy level (eg. [5]).

Some other studies have focused on merging geographical routing with energy-awareness. In [6], the energy model of a solar harvester is incorporated into geographic routing. In [7], the dissemination scope of topological information is adjusted adaptively based on the solar energy avaialable over the next period and packets are routed according to their QoS constraints. A distributed routing scheme is presented which finds the shortest path to the sink [8]. It then maps the available energy to a local distance penalty on each path and solves the local minimum problem by a distributed penalty metric.

Traditional routing does not reach its full potential in WSN-HEAP because the stochastic variations in the environmental energy causes uncertainty about the near future and results in asynchronous schedules. Therefore the set of potential next-hop nodes cannot be known at a reasonable cost prior to sending the packet. In this case, opportunistic routing seems to be a proper solution. By benefiting from the nature of the wireless channel, packet is broadcasted at each step and then any decision on the next hop selection is deferred until the successful reception by the available neighbors. After that the routing comprises: (a) filtering potential candidates (b) priority designation to filtered candidates and (c) coordinated transmission based on priority.

The idea of exploiting opportunistic routing for WSN-HEAP was first exploited in [9]. It proposes EHOR in which the filtering is done based on geographical advancement. Among the filtered candidates, priority is determined individually based on the distance to the sink and the residual energy using weighted averaging. After that, coordination takes place in a time-slotted manner where the higher priority nodes are assigned to earlier slots. In the assigned slot, each node transmits the data packet only if it has not overheard the others' transmission in the previous slots. Duration of each slot is fitted to the transmission time of a data packet and the number of slots is determined by the number of geographical regions which is computed using the average harvesting rate. The energy management model only considers the current and average harvesting rate and does not take into account the future energy availability.

In this paper we present and evaluate an Opportunistic Routing algorithm with Adaptive Harvesting-aware Duty Cycling (OR-AHaD) for WSN-HEAP. The key contributions are:

First, a coordination message is used by the winner candidate instead of the original data packet to reduce coordination delay. Second, the energy model is modified to incorporate the exchange of the coordination messages. Based on that, an energy management model is proposed that adaptively adjusts the duty cycle by considering the harvesting rate in the near future.

The remainder of this paper is organized as follows. Section II presents the network conditions and the energy model under which the proposed algorithm is evaluated. Section III describes the OR-AHaD algorithm and its features in detail. The performance evaluation results using simulation are discussed in Section IV. At last, conclusions are drawn in Section V.

II. NETWORK MODEL AND ASSUMPTIONS

The network model must capture the energy model which consists of the energy consumption and the energy replenishment. It also has to describe the deployment topology and the traffic properties of the network.

A. Topology and Traffic characteristics

The network consists of $n_{sensor} = 20 - 300$ sensor nodes in a 1D area spanning $d_{max} = 300m$. Only one of the sensor nodes act as the sending source and the other ones play the role of forwarding relays in the multihop routing. This is realistic in event-triggered applications such as target tracking. The sink node is located at the origin of the coordinate system. The transmission range of the nodes is assumed to be $R = 70m$ (with $PDR = 10\%$) as in [9]. All the nodes are equipped with GPS.

We study a saturated network. The data packet and the coordination message size are $s_d = 100bytes$ and $s_c = 15bytes$, respectively. In this network the channel rate is $r = 250Kbps$. The propagation delay and the hardware turnaround time (from receive to transmit) are $t_{prop} = 0.008ms$ and $t_{tu} = 0.192ms$, respectively.

B. Energy Model

Sensor nodes are powered by energy harvesters. The specification of TI energy harvesting sensor nodes are presumed in our scenarios [10]. Energy is harvested at all times. For the energy storage, a $12\mu Ah$ Enerchip rechargeable battery is used with output voltage of $3.8V$ [11]. The sink is connected to power supply and does not require recharging.

The energy model of a sensor node is illustrated in Fig. 1. Each node runs through a number of cycles, each consisting of one inactive period, followed by a couple of active periods.

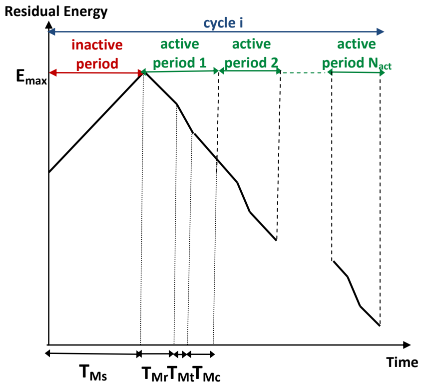


Fig. 1. Energy model of a sensor node

We assume that the nodes are aware of their harvesting rate in the current period and can also predict the rate of the next period. An exponential distribution is used to model the time it takes for a depleted node to get charged to a level denoted as E_{max}. The parameter of this exponential distribution is the inverted average charge time (computed using E_{max} and the given average harvesting rate of the scenario denoted as $P_{har-avg}$). If the charge time in the active period i is $T_{har-act(i)}$, then the harvesting rate in that period can be derived from $P_{har-act(i)} = \frac{E_{max}}{T_{har-act(i)}}$.

In the inactive period, node remains in sleep mode M_s until the battery is charged to E_{max}. The power consumption in this mode is negligible since node's components are mostly shut down. Duration of the inactive period t_{M_s}, depends on the harvesting rate in that period.

The active period initiates in receive mode M_r with duration t_{M_r}. This mode ends either when it is time for a node to forward a received packet or when the timer indicating the maximum time goes off. The power consumption in this mode is $P_{rx} = 72.6mW$. After that it will shift to transmit mode M_t for t_{M_t}. If the sensor node is a data source it transmits a new packet unless it has to forward a received packet at that time. However, if it is a relay node, it sends a coordination message followed by the data packet which is due for transmission. The node uses carrier sensing before sending a packet to make sure the channel is idle. The power consumed in this mode is $P_{tx} = 83.7mW$. Once the transmit mode is over, node transits to coordination mode M_c, where it waits for the specified time t_{M_c} to receive a coordination message for the packet forwarded earlier to make sure it has progressed. The power usage is the same as receive mode.

We let $min(t_{M_r})$, $max(t_{M_r})$ and $E[t_{M_r}]$ be the minimum, maximum and expected time in the receive mode, respectively. Now the minimum, maximum and expected energy consumption of the node in each active period are computed as:

$$min(E_{con-act}) = min(t_{M_r}) \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \quad (1)$$

$$max(E_{con-act}) = max(t_{M_r}) \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \quad (2)$$

$$E[E_{con-act}] = E[t_{M_r}] \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \quad (3)$$

And the energy harvested in the active period i is:

$$E_{har-act(i)} = (t_{M_r} + t_{M_t} + t_{M_c}) \cdot P_{har-act(i)} \quad (4)$$

III. OPPORTUNISTIC ROUTING WITH ADAPTIVE HARVESTING-AWARE DUTY CYCLING (OR-AHAD)

To describe OR-AhaD in details, first different phases of routing in the proposed algorithm are explained. Then zoning and coordination messages and their application are discussed.

At last the energy management decision making which adaptively adjusts the duty cycle of the nodes is presented.

A. Routing Algorithm

In the initial phase of OR-AHaD, the candidates who have received the packet but are not closer to the sink than the previous hop are filtered. In the subsequent step, priority designation is done via geographical zone assignment. Nodes residing in the zones closer to the sink have higher transmission priorities. Afterwards, a timer-slotted coordination strategy is applied and the candidates are delayed according to their priorities. The number of slots is equal to the number of zones and the duration of each slot is fitted for sending a short coordination message.

We let the distance from the previous hop to the current candidate be d_{pre} and the number of zones as N_{zones}. The time slot for transmitting the coordination message based on the distance factor can be computed using:

$$s_{no} = \begin{cases} 1 + \lceil (1 - \frac{d_{pre}}{R}) \cdot (N_{zones} - 1) \rceil, & d_{pre} \leq R \\ 1, & R < d_{pre} \end{cases} \quad (5)$$

The performance can be improved by improvising a scheme to adjust the final priority based on the residual energy, in addition to the distance from the sender. Accordingly if the residual energy of the node after receiving a packet is E_{res}, then the transmission slot denoted as s_{no} can be derived from:

$$s_{no} = \gamma \cdot s_{dist} + (1 - \gamma) \cdot s_{ene} \quad (6)$$

where, γ is a weighting factor and s_{ene} is calculated using:

$$s_{ene} = \lceil \frac{E_{res}}{E_{max}} \cdot N_{zones} \rceil \quad (7)$$

B. Zoning and Coordination Messages

Applying geographical zoning reduces the coordination delay. Instead of assigning slots per node, we designate it per zone. Therefore, the overall interval is shortened. It also enables the nodes to individually determine their transmission slots without any required information about the other candidates' priorities.

There is a trade-off in determining the number of zones. If more than one active node falls in each zone, collision can take place since the nodes in the same zone are assigned the same transmission slot. However, if no active node resides in some zones, there would be empty slots which unnecessarily increases delay. Therefore, N_{zones} must be computed in such a way that one and only one active node resides in it with high probability.

We use approximations in computing the number of zones. One zone is dedicated to the candidates outside the transmission range of the source who still might receive the data packet with low probability. As for the rest, assuming that nodes are uniformly distributed across the deployment area, the number of candidates who are closer to the sink than the previous hop and fall within the transmission range would be $n_{sensor} \cdot \frac{r}{d_{max}}$.

Assuming each node is in the active period with probability $prob_{act}$ then N_{zones} must be equal to the number of active nodes to serve our purpose and hence, it can be derived from:

$$N_{zones} = [prob_{act} \cdot n_{sensor} \cdot \frac{R}{d_{max}}] + 1 \quad (8)$$

This equation is similar to the one for computing the number of regions in [9]. However, $prob_{act}$ must be recomputed because the energy model of the nodes is different. Before deriving an equation for $prob_{act}$, we first have to describe the application of the coordination messages and compute the time node spends in the active and inactive periods.

Upon reception of a packet in mode M_r, the filtered candidate computes its priority and starts its coordination timer. From the start of the interval it keeps listening to the channel to see if any active candidate with higher priority declares to be the next official hop. Once a node overhears the declaration in earlier slots, it abstains from forwarding and cancels out its coordination timer. In the proposed algorithm instead of sending out the data packet itself, special coordination messages are used. In this way each slot can be fixed for transmission of a short $s_c = 15 bytes$ coordination message at MAC layer instead of the data packet which is $s_d = 100 bytes$. As a result the overall coordination time is reduced even more. According to this we have two kinds of slots. One for transmitting the data packets denoted as $slot_d = t_{prop} + \frac{s_d}{r} + t_{tu}$ and the other one for transmitting the coordination messages specified as $slot_c = t_{prop} + \frac{s_c}{r} + t_{tu}$.

In mode M_r, it takes as long as $slot_d$ to fully receive a data packet. Afterwards, node computes its transmission slot. In the best case it is designated the first slot so it immediately transfers to M_t. However, in the worse case it is in the zone with the lowest priority and hence, has to stay in this mode during the whole coordination interval. In conclusion, the lower and upper bound and the expected value for t_{M_t} are:

$$min(t_{M_r}) = slot_d \quad (9)$$

$$max(t_{M_r}) = slot_d + N_{zones} \cdot slot_c \quad (10)$$

$$E[t_{M_r}] = \frac{min(t_{M_r}) + max(t_{M_r})}{2} \quad (11)$$

After sending the coordination message, the winner immediately proceeds with forwarding the packet. Transmission of the coordination message and the data packets take place in mode M_t with the fixed duration $t_{M_t} = slot_d + slot_c$.

Having transmitted the packet, the node transits to mode M_c and waits along for the reception of the confirmation message by the next hop candidate. This process takes as long as the coordination interval which is equal to $t_{M_c} = N_{zones} \cdot slot_c$.

According to the above equations, the minimum, maximum and expected value for the total time in the active period denoted as t_{act} can be derived from:

$$min(t_{act}) = min(t_{M_r}) + t_{M_t} + t_{M_c} \quad (12)$$

$$max(t_{act}) = max(t_{M_r}) + t_{M_t} + t_{M_c} \quad (13)$$

$$E[t_{act}] = E[t_{M_r}] + t_{M_t} + t_{M_c} \tag{14}$$

After going through a number of active periods, N_{act}, which is based on the output of the adaptive algorithm in Section III-C, node finally goes to inactive mode and remains there until it is fully charged. The amount of energy that needs to be replenished depends on the number of active periods and the energy left at the end of each period. The expected value of t_{M_s} (same as t_{inact}) is calculated from:

$$E[t_{M_s}] = \frac{E_{max} - E[N_{act}]\dot{(}E[E_{con-act}] - P_{har-avg} \cdot E[t_{act}])}{P_{har-avg}} \tag{15}$$

With these information the probability of being in the active mode for a node in (8) can finally be computed as:

$$prob_{act} = \frac{E[t_{act}] \cdot E[t_{M_r}]}{E[N_{act}] \cdot E[t_{act}] + E[t_{inact}]} \tag{16}$$

Rearranging (8) and (16), the value of N_{zones} can be obtained by solving a quadratic equation which always has a nonnegative result.

C. Adaptive Harvesting-aware Duty Cycle Management

In WSN-HEAP the challenge is exploiting the available environmental energy to meet the required QoS and hence, it is important to adapt to the changing environment. Here we propose a harvesting-aware energy management model which determines node's schedule adaptively.

As presented in Section II-B, each sensor node runs through a number of cycles which is composed of an inactive period, followed by a number of active periods. Instead of using a fixed number of active periods in each cycle throughout the scenario, we use the knowledge of the current period and the predicted next period rates as two environmental factors to decide whether to end the cycle and transit to the sleep mode or continue this cycle by going to the next active period.

We use three energy factors as an input to the decision making model: (a) the residual energy at the end of the current period (b) the available energy in the next period which is computed using (4) and (c) the minimum and maximum energy consumption in a single active period which can be derived from (1) and (2), respectively.

Assuming at the end of the active period $i-1$ of a cycle, the residual energy is $E_{res-act(i-1)}$ then the residual energy at the end of the next period, if we decide to proceed to active period i, is:

$$E_{res-act(i)} = E_{res-act(i-1)} + E_{har-act(i)} \tag{17}$$

Two thresholds $E_{lo} = min(E_{con-act})$ and $E_{hi} = max(E_{con-act})$ are defined as the minimum and maximum energy consumption in each active period. Then using probabilistic decision making, the probability of going to the next cycle based on the environmental energy factors is p_e. According to (18), if $E_{res-act}(i)$ is less than E_{lo}, node definitely ends the cycle and goes to the inactive period. If it is more than E_{hi}, it definitely proceeds to the active period i. Otherwise, the probability is decreased linearly.

$$p_e = \begin{cases} 1, & E_{res-act(i)} < E_{lo} \\ \frac{E_{hi} - E_{res-act(i)}}{E_{hi} - E_{lo}}, & E_{lo} < E_{res-act(i)} < E_{hi} \\ 0 & E_{hi} < E_{res-act(i)} \end{cases} \tag{18}$$

IV. PERFORMANCE EVALUATION

We use QualNet Network Simulator [12] to evaluate the performance of OR-AHaD. The performance metrics used for evaluation are: (a) *Goodput*: rate of receiving non-duplicate data packets at the sink (b) *Efficiency*: ratio of non-duplicate data packets to all the data packets received at the sink.

We first evalute the performance of OR-AHaD under different values of γ and compare it with EHOR. Then we study the performance of OR-AHaD under different harvesting rates.

A. Comparing OR-AHaD with EHOR

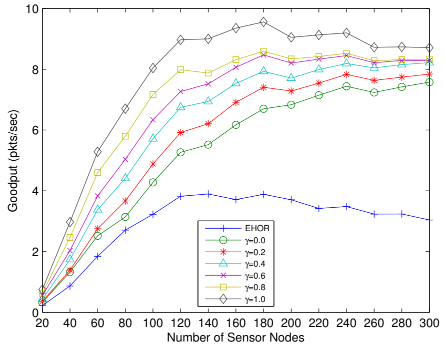
To assess the performance gain of the proposed energy management model and use of the coordination messages, we compare our algorithm with EHOR. We set β to 0.6 for EHOR which achieves high performance in most of the scenarios [9]. We also change the value of γ, to see how it affects the overall performance of OR-AHaD.

The simulation results are presented in Fig. 2. Regardless of the value of γ, OR-AHaD achieves much higher goodput in comparison to EHOR. In OR-AHaD source node has the chance of sending a new packet at the end of each active period, whereas in EHOR the timing is at the end of the receive state which is normally longer than the duration of active period. Therefore under saturated condition, the source sending rate is higher in OR-AHaD. Also, by exploiting the adaptive energy management model, a more suitable candidate set is active for collaboration in the packet forwarding. Efficiency is also higher in OR-AHaD because the rate of duplicate packets is limited by using coordination messages. Even at the last hop, when sink receives a data packet it sends out a coordination message like the previous hops along the path. whereas, in EHOR the sink does not notify the neighbors.

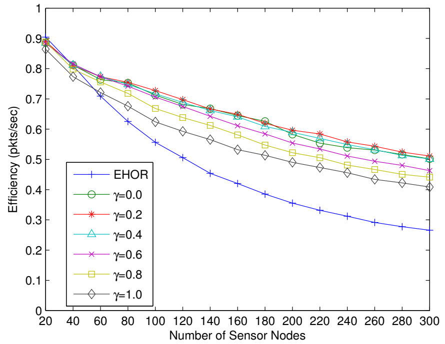
The key parameter in the design of OR-AHaD is γ. Increasing γ, improves goodput. By giving more weight to distance factor, advancement per hop increases so packets suffer less delay. The energy will not be a problem because the energy management model already takes care of this and manages candidate set adaptively according to the environmental energy factors. However as γ increases, efficiency drops down. When $\gamma = 1.0$, nodes outside the transmission rage of the source are assigned the highest priority. When they use notification messages, many of the other candidates are not informed because of being outside the overhearing zone and unnecessarily transmit the packet in the future slots. As a result the rate of receiving duplicate packets at the sink, increases.

B. Effect of Varying Average Harvesting Rate

We study the effect of changing the average harvesting rate which symbolizes the wide range of energy harvesters and



(a) Goodput



(b) Efficiency

Fig. 2. Comparing performance results of OR-AHaD with EHOR

various temporal and spatial conditions. Fig. 3 illustrates the scenario with 200 sensor nodes. γ is set to 1.0 to achieve the highest goodput and $P_{har-avg} = 3 - 27mW$.

As the rate increases, the nodes spend less time in the inactive period. The multiplicity of the zones grows because of the increase in the number of nodes that are not asleep at the time. This extends the candidate set and as a result enhances goodput. As for efficiency, it decreases slightly because the increment in the number of zones, scales-up the probability of duplicate reception.

V. CONCLUSION

In this paper we presented OR-AHaD, an opportunistic routing algorithm for WSN-HEAP that prioritizes the candidates based on their zones and their residual energy. We introduced the use of coordination messages and proposed an energy management model which exploits the estimated harvesting rate in the near future to adjust the duty cycle adaptively. The simulation results show that goodput and efficiency are increased in comparison to EHOR. In addition, the proposed algorithm performs well under different harvesting rates.

Further work involves extending the algorithm to multi-source scenarios and 2D deployment areas, as well as modeling the effect of prediction accuracy in routing performance.

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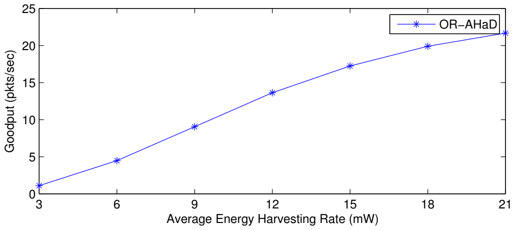
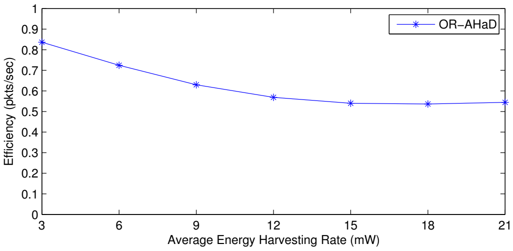


(a) Goodput



(b) Efficiency

Fig. 3. Performance results of varying average harvesting rates

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