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OR-AHaD: An Opportunistic Routing Algorithm for 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 book chapter, 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 which 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.

Keywords: opportunistic routing, harvesting-aware, wireless sensor networks.

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2.1 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 as their main source of power and their lifetime was limited to their battery life. However, recently with the emergence of energy harvesting technologies for embedded systems, the trend has headed towards wireless sensor networks which are powered by ambient energy harvesters (WSN-HEAP) with the advantages of being cheaper, easier to deploy, more environmentally friendly and most importantly capable of being recharged many times [17].

Different types of energies such as solar, thermal and vibrational can be exploited using a variety of energy harvesting devices. Availability of the energy depends on many factors including the internal structure of the harvesting device as well as temporal conditions and the location of deployment. The energy harvesting capability of current technologies starts from tens of μW but does not exceed several mW. For instance, a 10 cm^2 electromagnetic vibrational device can harvest on average 40 μW, whereas a typical indoor solar device of the same size can harvest up to but no more than 37 mW [17]. The typical power consumption of a node's transceiver during its operation is much more than the average replenishment rate (around 3 to 20 times) which is usually stochastic in nature. Consequently, the energy harvesting sensor node cannot remain active continuously and needs to shutdown from time to time. Based on these energy characteristics, it is important to develop novel energy management models and routing protocols that consider the temporal and spatial variations of the available environmental energy.

Several routing strategies have been suggested for WSN-HEAP. Until recently, most of them focused on traditional routing techniques which are not very suitable for such networks considering the stochastic variations in harvesting rates. In order to overcome, opportunistic routing has been suggested to best exploit the available environmental energy and increase goodput by relying on the broadcast nature of the wireless medium.

However, the existing proposal on opportunistic routing for WSN-HEAP has some limitations [4]. Firstly, the energy management model determines the duty cycle of each node independently of the future availability and assigns schedules only based on the average and current harvesting rate. Moreover, coordination among the candidates for the next hop is time consuming and therefore, goodput is not as high as it can be.

In this book chapter, we present and evaluate an Opportunistic Routing algorithm with Adaptive Harvesting-aware Duty Cycling (OR-AHaD). The key contributions are: First, a coordination message is used instead of the original data packet to shorten the overall coordination interval. Second, the energy model is modified to incorporate the exchange of coordination messages. Based on that, an energy management model is proposed that adaptively adjusts the duty cycle by considering not only the current, but also the near future availability of energy. Third, the number of geographical zones, is recomputed based on the new energy model.

The remainder of this chapter is organized as follows. The related work is presented in Section 2.2. Next, Section 2.3 presents the network conditions and energy model under which the proposed algorithm is evaluated. Followed by that, Section 2.4 describes OR-AHaD algorithm and its features in detail. The performance evaluation results using simulation are discussed in Section 2.5. Then in Section 2.6, the remaining open challenges in this area are argued. Lastly, conclusions are drawn in Section 2.7.

2.2 Related Work

In literature, a number of routing solutions have been proposed for WSN-HEAP. They are mostly traditional techniques aimed for increasing efficiency by optimizing energy consumption or goodput by considering geographical locations. On the other hand, recently the idea of opportunistic routing has been brought up in this context. It promotes taking advantage of the broadcasting nature of wireless channels and making per-hop decisions after packet reception. In this section, we will have a brief look over the existing work.

2.2.1 Traditional Energy-Aware and Geographical Routing

The most common approach towards routing in wireless networks is the conventional routing where the routing path is determined before or upon transmission of the packet based on a cost metric reflecting the routing goals. WSN-HEAP is no exception to that with the main attention towards geographical distances and energy efficiency. Some have defined routing as an energy efficiency problem and worked on choosing energy efficient routes or integrating energy management functions, while others involved geographical advancement.

Some research studies have been carried out on power management of WSN-HEAP (eg. [8, 12, 14]). They mostly rely on designing low overhead algorithms for the prediction of the future harvesting rate. In [14], a method is proposed for predicting the future availability of energy based on the current energy sample and samples of previous days for solar harvesters meanwhile taking into account the changes in weather conditions. Another study extends power management for solar harvesters to real-time applications using time series and DVFS techniques. Regression analysis, moving average and exponential smoothing are the three methods suggested for run-time prediction in [12]. Having a time-stamped value of sunlight intensity, a linear regression model can predict the future harvesting rate. Moving average is another method that forecasts based on the average value of the past observations. Exponential smoothing operates the same way as moving average, only with weights relative to the freshness of the past observations.

Several energy-aware routing solutions have been proposed for WSN-HEAP. The authors of [9] described the energy efficiency problem as achieving maximum workload under available energy rather than increasing lifetime which was tailored to battery-powered sensors and sought for an optimal routing solution based on that. The probability of forwarding the packet on each link is proportional to the the maximum flow through that link. In another work, a mathematical framework was developed to parameterize the real characteristics of environmental energy. Then analytical strategies were associated with it to evaluate the benefits of energy-aware routing in the presence of renewable energy sources [11]. A cost value is computed for every node based on the battery capacity, available energy, harvesting and consumption power and then the shortest path is calculated accordingly.

While a few of the existing studies explicitly consider the time varying environmental energy such as the above-mentioned, many of them still concentrate only on the residual energy level. For instance, a modified version of AODV is designed which uses the weighted value of the residual energy and hop count as the metric for battery powered sensor networks with complementary solar harvesters to increase the battery lifetime [3].

Some other studies have focused on merging geographical routing with energy-awareness. Geographical routing with the benefit of low overhead, scalability and high capacity has shown to be a proper choice for many WSN applications that require location awareness. In geographical routing, the decision on data progress is based on the location information of the node, its neighbors and the sink. Having this information, data can be directed to a particular region and progress towards the sink at each hop. In [19], the energy model of a solar harvester is incorporated into geographic routing. Nodes are assumed to periodically exchange their current residual energy and expected harvesting rate with their neighbors. Based on the gathered information, each node forwards the received packet to the neighbor that minimizes the cost based on the progressive distance and effective energy. In [13], the dissemination scope of topological information is adjusted adaptively based on the solar energy budget over the next period and packets are routed according to their QoS constraints related to delay sensitivity. A distributed routing scheme is presented which aims for the energy optimized routes [7]. Initially, this routing scheme finds all the shortest paths which are also the ones with the least energy consumption. Then it maps the available energy to a local distance penalty on each path and solves the local minimum problem by a distributed penalty metric. The final shortest path is recomputed considering these penalties and the stochastic nature of harvesting rate is considered through some global parameters.

Traditional routing does not reach its full potential in WSN-HEAP because the stochastic variation in 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.

2.2.2 Opportunistic Routing and EHOR

In order to overcome the limitations of traditional routing algorithms for WSN-HEAP, opportunistic routing has been suggested. By benefiting from the nature of the wireless channel, a packet is broadcasted at each step and then any decisions on the next hop selection is deferred until the successful reception by the available neighbors. After that the routing comprises: (a) filtering the potential candidates (b) priority designation to the filtered candidates and (c) coordinated transmission based on priority [6].

The idea of exploiting opportunistic geographic routing for WSN-HEAP was first proposed in [4]. To the best of our knowledge, this is the only work that has been done in this area up to now. It proposes EHOR, a novel routing technique that aims at improving the shortcomings of conventional opportunistic routing schemes suited for battery-powered WSN.

EHOR uses a regioning approach. Filtering is done based on geographical advancement. It means that from the nodes that have successfully received the packet, only the ones that are closer to the destination than the previous hop are eligible to be a candidate. 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, the node transmits the data packet only if it has not overheard others' transmissions in the previous slots.

The performance of opportunistic routing in such networks also depends on the associated energy model and the schedule of the nodes. In EHOR, at the beginning of each cycle, each node remains inactive until the stored energy reaches a defined threshold and therefore, the duration depends on the current harvesting rate. After that, the node becomes active for a fixed amount of time which is the same in every cycle and is dependent on the average harvesting rate.

Two limitations of EHOR are:

- Future availability of the energy is not taken into consideration and the schedule of a node is only based on the current and average harvesting rate. Therefore, the energy is not managed optimally.
- Even though regioning is applied and coordinating delay is reduced, it is still not maximally reduced and therefore, affects the goodput.

The work presented in this book chapter is a follow up on EHOR and is aimed at addressing the above mentioned limitations.

2.3 Network Model and Assumptions

The network model must captures the energy model which consists of energy consumption and energy replenishment. It also describes the deployment topology and traffic properties of the network. The notations used in this paper are summarized in Table 2.1.

2.3.1 Topology and Traffic Characteristics

The network consists of $n_{sensor} = 20$–300 sensor nodes in a 1D area spanning $d_{max} = 300$ m. All of the sensor nodes play the role of forwarding relays in a multihop routing scenario but only one of them acts as the data source. This is realistic in event-triggered applications such as target tracking. The sink node is located at the origin of the coordinate system. $R = 70$ m is the maximum transmission range of the node where packet delivery ratio is above 10% as in [4]. We use Log-normal shadowing and Ricean fading to model the radio propagation. All the nodes are equipped with GPS.

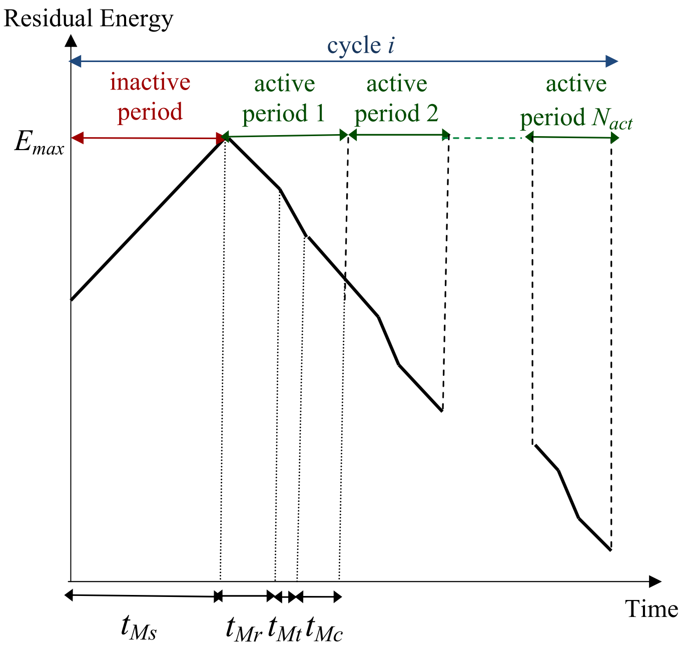


Figure 2.1 Energy model of a sensor node.

We study a saturated network where the source either forwards a received data packet or sends a new data packet in each active period explained in Section 2.4.2. The data packet and the coordination message size are $s_d = 100$ bytes and $s_c = 15$ bytes, respectively. In this network, the channel rate is $r = 250$ Kbps. The propagation delay and the hardware turn-around time (from receive to transmit) are $t_{prop} = 0.008$ ms and $t_{tu} = 0.192$ ms, respectively.

2.3.2 Energy Model

Sensor nodes are powered by energy harvesters. The specification of TI energy harvesting sensor nodes are assumed in our scenarios [18]. Energy is harvested at all times. For the energy storage, a 12μAh Enerchip rechargeable battery is used with output voltage of 3.8 V citeEnerchip. Sink is connected to the power supply and does not require recharging.

The proposed energy model of a sensor node is as illustrated in Figure 2.1. Each node runs through a number of cycles. Each cycle consists of one in-

Table 2.1 Notations used for describing OR-AHaD.

Symbol	Denotes
d_{max}	Length of the deployment area
d_{pre}	Candidate's distance from the previous hop
$E_{con-act}$	Energy consumed in an active period
$E_{con-act}$	Energy consumed in an active period
$E_{har-act(i)}$	Energy harvested in active period i
E_{max}	Energy of a fully charged sensor node
$E_{res-act(i)}$	Residual Energy at the end of active period i
$E_{av(i)}$	Available energy for active period i
M_j	Sensor node's mode ($j = s$: sleep, $j = r$: receive, $j = t$: transmit, $j = c$: coordination)
n_{sensor}	Number of sensor nodes
N_{act}	Number of active periods in a cycle
N_{zones}	Number of geographical zones
p_{act}	Probability of being active and in the receive mode
$p_{end-act}$	Probability of ending a cycle and going to inactive mode
$P_{har-act(i)}$	Harvesting rate in active period i
$P_{har-avg}$	Average harvesting rate
P_{rx}	Receive power of the sensor node
P_{tx}	transmission power of the sensor node
r	Transmission rate of the sensor node
R	Maximum transmission range where packet delivery ratio is above 10%
s_c	Size of the coordination packet
s_d	Size of the data packet
s_{dist}	Slot number for candidate transmission based on the distance factor
s_{ene}	Slot number for candidate transmission based on the energy factor
s_{no}	Final slot number for candidate transmission
$slot_c$	Slot duration for sending a coordination packet
$slot_d$	Slot duration for sending a data packet
t_{act}	Duration of an active period
$t_{har-act(i)}$	Charge time in active period i
$t_{har-avg}$	Average charge time of a depleted node to level E_{max}
t_{inact}	Duration of an inactive period
t_{M_j}	Duration of mode M_j
t_{prop}	Maximum propagation delay
t_{tu}	Hardware turnaround delay from receive to transmit state and vice versa
γ	Candidate priority weight between distance and energy factors

active period, followed by a couple of active periods. The number of active periods in a cycle is determined by an adaptive harvesting-aware duty cycling algorithm which will be introduced later in this chapter.

The duration of inactive period t_{M_s}, depends on the harvesting rate which is different in each period. 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, the node remains in sleep mode M_s until the battery is charged to E_{max}. The power consumption in this mode is negligible since the node's components are mostly shut down. The 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}. The node waits to receive a data packet. The power consumption in this mode is $P_{rx} =$ 72.6 mW. After that it will shift to transmit mode M_t to send coordination message and forward the received packet. The interval of this mode is t_{M_t} and the power consumed is $P_{tx} = 83.7$ mW. Once the transmit mode is over, the 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 the $min(t_{M_r})$, $max(t_{M_r})$ 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 a node in each active period is computed as:

$$min(E_{con-act}) = min(t_{M_r}) \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \tag{2.1}$$

$$max(E_{con-act}) = max(t_{M_r}) \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \tag{2.2}$$

$$E[E_{con-act}] = E[t_{M_r}] \cdot P_{rx} + t_{M_t} \cdot P_{tx} + t_{M_c} \cdot P_{rx} \tag{2.3}$$

The amount energy harvested in active period i is:

$$E_{har-act(i)} = (t_{M_r} + t_{M_t} + t_{M_c}) \cdot P_{har-act(i)} \tag{2.4}$$

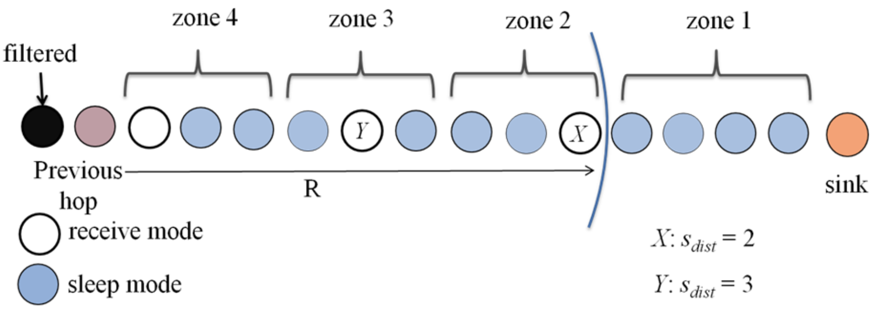


Figure 2.2 Transmission priority based on the distance factor in a 1D area with 4 zones.

2.4 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. Lastly the energy management model which adaptively adjusts the duty cycle of the nodes is presented.

2.4.1 Routing Algorithm

As we said earlier in Section 2.2.1, any opportunistic routing protocol is composed of three phases. 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. Detailed information regarding zones can be found in Section 2.4.2.

Transmission priorities can be computed as in [4]. We let the distance from the previous hop to the current candidate be d_{pre} and the number of zones as N_{zones}. The slot number for transmitting the coordination message based on the distance factor, s_{dist}, is the same as the zone number. Zones closer to the destination have higher priorities and consequently are assigned earlier slots as illustrated in the example in Figure 2.2. Each candidate can compute s_{dist} using

$$s_{dist} = \begin{cases} 1 + \lceil (1 - \frac{d_{pre}}{R}) \cdot (N_{zones} - 1) \rceil, & d_{pre} \leq R \\ 1, & R < d_{pre} \end{cases} \tag{2.5}$$

The performance can be improved by improvising a scheme to adjust the final transmission priority based on the residual energy, in addition to distance from the sender as in [4]. Accordingly if the residual level of the node after receiving the packets is E_{res}, then the final transmission slot denoted as s_{no} can be calculated using

$$s_{no} = \gamma \cdot s_{dist} + (1 - \gamma) \cdot s_{ene} \tag{2.6}$$

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

$$s_{ene} = \left\lceil \frac{E_{res}}{E_{max}} \cdot N_{zones} \right\rceil \tag{2.7}$$

2.4.2 Zoning and Coordination Messages

We apply the concept of geographical zoning as in [4], for two main reasons. The first one is reducing the coordination delay which is a major challenge in timer-based coordination methods. Instead of assigning slots per node, we designate it per zone. Therefore, the overall interval is shortened. The second advantage is enabling nodes to individually determine their priorities with no extra knowledge required from the other candidates.

There is a trade-off between the end-to-end delay and the the probability of collision in determining the number of zones [4]. N_{zones} must be computed in such a way that one and only one active node resides in it. We use approximations in computing the number of zones. We dedicate one zone 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 sink than previous hop and fall within the transmission range would be $n_{sensor} \cdot \frac{R}{d_{max}}$.

Assuming each node is in 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 obtained by solving

$$N_{zones} = \left\lceil prob_{act} \cdot n_{sensor} \cdot \frac{R}{d_{max}} \right\rceil + 1 \tag{2.8}$$

This equation is similar to the one for computing the number of regions in [4]. However, $prob_{act}$ must be computed differently because the energy model and schedule of the nodes are different. Before deriving an equation for $prob_{act}$, we first have to describe the application of coordination messages and compute the time the node spends in active and inactive periods.

Upon reception of a packet in mode M_r, the filtered candidate computes its priority and start 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 declaration in earlier slots, it abstains from forwarding and resets its coordination timer and continues listening for other incoming data packets until the maximum receive time is over. 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 data packets denoted as $slot_d = t_{prop} + \frac{s_d}{r} + t_{tu}$ and the other for transmitting coordination messages specified as $slot_c = t_{prop} + \frac{s_c}{r} + t_{tu}$.

Mode M_r ends either when it is time for a node to forward a received packet or when the timer indicating the maximum time goes off. In this mode, it takes as long as $slot_d$ to fully receive a data packet. Afterwards, the node computes its transmission slot. In the best case it is designated the first slot so it immediately transfers to M_t. Therefore, the minimum time in the receive mode is:

$$min(t_{M_r}) = slot_d \tag{2.9}$$

However, in the worst case, it is in the zone with the lowest priority and hence has to stay in this mode during the whole coordination interval. The maximum time that a node is allowed to stay in M_r, should be greater than the entire coordination interval in addition to $slot_d$. In this book chapter, we let the maximum time in the receive mode be:

$$max(t_{M_r}) = slot_d + N_{zones} \cdot slot_c \tag{2.10}$$

The expected value for t_{M_t} can be computed based on 2.9 and 2.10:

$$E[t_{M_r}] = \frac{min(t_{M_r}) + max(t_{M_r})}{2} \tag{2.11}$$

The winner immediately proceeds to mode M_t. If it is only a relay node, it sends a coordination message followed by the data packet which is due for transmission. However, if it is also a data source and does not have a packet to forward at that time, it transmits a new data packet. The node uses carrier sensing before sending a packet to make sure the channel is idle. Transmission of coordination and data packets take place in this mode with the fixed duration t_{M_t}:

$$t_{M_t} = slot_d + slot_c \tag{2.12}$$

Having transmitted the packet, the node transits to mode M_c and waits for the reception of the coordination message from the next hop candidate. This process takes as long as the coordination interval:

$$t_{M_c} = N_{zones} \cdot slot_c \tag{2.13}$$

According to the above equations, the expected value for the total time in active period denoted as t_{act} is:

$$E[t_{act}] = E[t_{M_r}] + t_{M_t} + t_{M_c} \tag{2.14}$$

The Zoning Approach degrades the possibility of concurrent transmissions in a slot. However, in the case of collision, candidates in subsequent slots have the chance of forwarding the data packet. The probability of duplicate transmission is reduced by listening to the channel while others are sending out coordination messages, but cannot be avoided for the candidates outside the overhearing range.

After going through a number of active periods, N_{act}, which is based on the output of the adaptive algorithm in Section 2.4.3, 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:

$$E[t_{M_s}] = \frac{E_{max} - E[N_{act}]\dot{(}E[E_{con-act}] - P_{har-avg} \cdot E[t_{act}])}{P_{har-avg}} \tag{2.15}$$

With this information the probability of being in active mode for a node in (2.8) can finally be computed as the ratio of the average time in the receive mode to the average duration of a cycle:

$$prob_{act} = \frac{E[N_{act}] \cdot E[t_{M_r}]}{E[N_{act}] \cdot E[t_{act}] + E[t_{inact}]} \tag{2.16}$$

The duration of the receive mode and the whole cycle depends on $E[N_{act}]$, the average number of active periods in a cycle. Rearranging (2.8) and (2.16), the value of N_{zones} can be obtained by solving a quadratic equation in O(1) time, which always yields a nonnegative result.

2.4.3 Adaptive Harvesting-Aware Duty Cycle Management

In a battery-powered WSN for the purpose of energy conservation and increase in network lifetime, it is desirable that nodes spend most of their time in the sleep mode as long as they meet the QoS constraints. However, 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.

We presented the energy model of the node in Section 2.3.2. As we said 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 and near future energy availability to decide at the end of each period whether to end the cycle and transit to sleep mode or continue the cycle by going to the next active period.

We use three energy factors as input to the decision making model: (a) the residual energy at the end of the current period (b) the expected energy harvested during the next period which is computed using (2.4) based on the predicted value of $P_{har-act}$ and (c) the minimum and maximum energy consumption in a single active period which can be derived from (2.1) and (2.2), respectively.

We Assume at the end of active period $i-1$ of a cycle, the residual energy is $E_{res-act(i-1)}$ and the expected energy harvested during the next active period, if we decide to proceed, would be $E[E_{har-act(i)}]$. Consequently, the available energy for period i can be computed as:

$$E_{av(i)} = E_{res-act(i-1)} + E[E_{har-act(i)}] \tag{2.17}$$

We define two thresholds E_{lo} and E_{hi} as the minimum and maximum energy consumption in each active period:

$$E_{lo} = min(E_{con-act}) \tag{2.18}$$

$$E_{hi} = max(E_{con-act}) \tag{2.19}$$

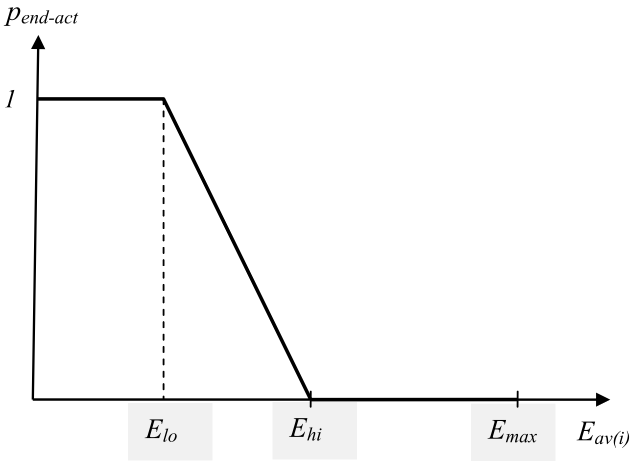


Figure 2.3 Probability density function of ending the cycle after active period $i-1$.

Then we use probabilistic decision making. The probability of going to the next cycle based on environmental energy factors is $p_{end-act}$ and the probability density function is illustrated in Fig 2.3 and formulated in 2.20. According to that, if $E_{av(i)}$ is less than E_{lo}, node definitely ends the cycle and goes to inactive period. If it is more than E_{hi}, it definitely proceeds to active period i. Otherwise, the probability is decreased linearly.

$$p_{end-act} = \begin{cases} 1, & E_{av(i)} < E_{lo} \\ \frac{E_{hi}-E_{av(i)}}{E_{hi}-E_{lo}}, & E_{lo} \leq E_{av(i)} < E_{hi} \\ 0 & E_{hi} \leq E_{av(i)} \end{cases} \tag{2.20}$$

2.5 Performance Evaluation

We use the QualNet Network Simulator [2] to evaluate the performance of OR-AHaD. We implement the proposed energy model and the routing algorithm into this simulator. The performance metrics used for evaluation are: (a) *Goodput*: rate of receiving non-duplicate data packets at sink (b) *Efficiency*: ratio of non-duplicate data packets to all the data packets received at sink (c) *Data Delivery Ratio*: ratio of the non-duplicate data packets received at sink to the data packets sent by the source and (d) *Hopcount*: the average number of hops traversed until a data packet is received at sink.

The network model including deployment and traffic characteristics are as explained in Section 2.3.1. In all scenarios, nodes are assumed to be TI energy harvesting sensor nodes with the specifications mentioned in Section 2.3.2.

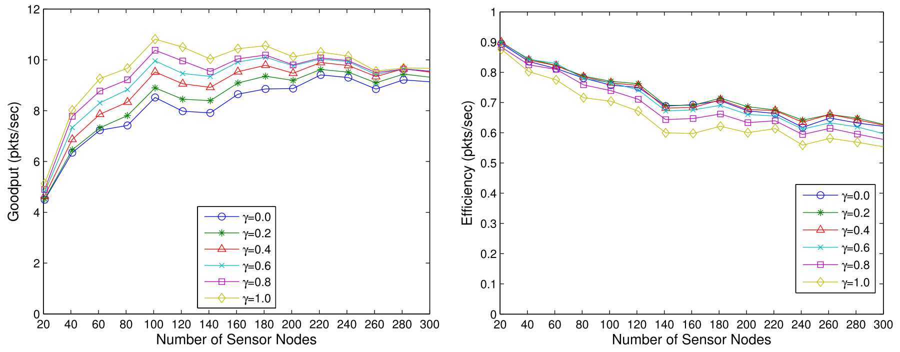
We first evaluate the performance of OR-AHaD under different scenarios. Then we compare its performance with EHOR. Data results presented in all the scenarios are derived by averaging 20 simulation runs using different seeds. The simulation time is 200 s with the warm-up period of 5 s.

2.5.1 Effect of Varying γ

The key parameter in the design of OR-AHaD is γ, $0 \leq \gamma \leq 1$, a factor that weights the transmission priority of a candidate between its distance to the sink and its residual energy. When $\gamma = 0$, candidates with lower residual energy are designated with higher transmission priorities. Here we study the effect of different values of γ on the overall performance of OR-AHaD. We set $P_{har-avg} = 10$ mW.

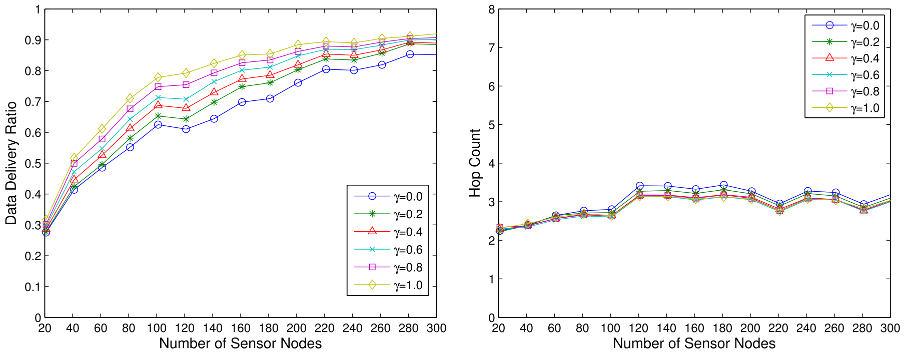
We first assume a scenario where all the sensor nodes including the source are randomly deployed. The simulation results are as illustrated in Figure 2.4. In another scenario, the source node is deployed such that it is furthest way from the sink while the other sensor nodes are still deployed in a random way and the simulations are repeated. The performance results are presented in Figure 2.5. The overall performance in the first scenario is better than the second one because multi-hop routing is more challenging when the distance between source and sink is high.

In both scenarios, increasing γ improves goodput and delivery ratio. By giving more weight to the distance factor, advancement per hop increases so packets suffer less delay and the network does not get too congested. The limitation of energy will not pose much of a problem because the energy management model already takes care of this and manages the candidate set adaptively according to environmental energy factors. Hopcount also decreases because fewer distant candidates from sink are assigned with higher priorities. However as γ increases, the efficiency drops. When $\gamma = 1.0$, the nodes outside the transmission rage of the source are designated with the highest priority. When they use coordination messages to inform other candidates, many of them are outside the overhearing zone and retransmit the packet in the following slots. As a result, the rate of receiving duplicate packets at the sink, increases and efficiency drops.



(a) Goodput

(b) Efficiency



(c) Delivery Ratio

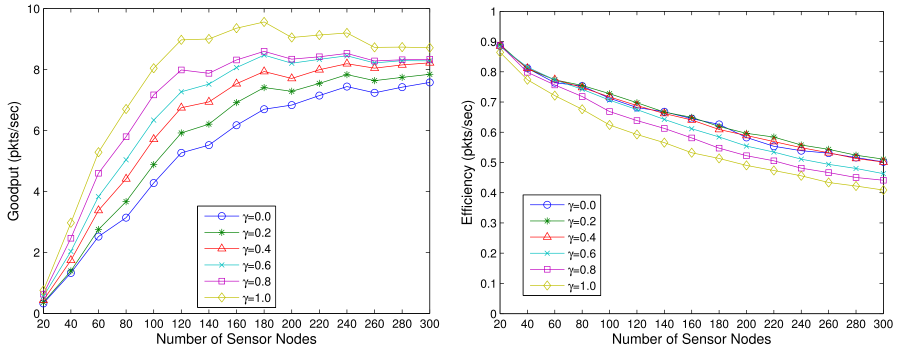
(d) HopCount

Figure 2.4 Performance results of varying γ (source deployed randomly).

2.5.2 Effect of Varying Average Harvesting Rate

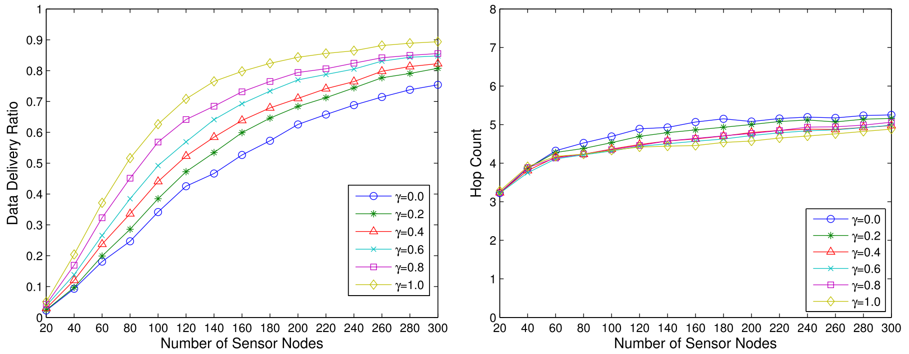
In this scenario we study the effects of changing the average harvesting rate which symbolizes a wide range of energy harvesting devices and various temporal and spatial conditions. Figure 2.6 illustrates the scenario with 300 sensor nodes, $P_{har-avg} = 3\text{–}27$ mW. γ is assumed it to be 1.0 which gives the highest goodput. Sensor nodes including the source are randomly deployed.

As the rate increases, nodes spend most of their time in active mode rather than inactive mode. The multiplicity of zones grows because of the increase in the number of nodes that are not asleep. This extends the candidate set



(a) Goodput

(b) Efficiency

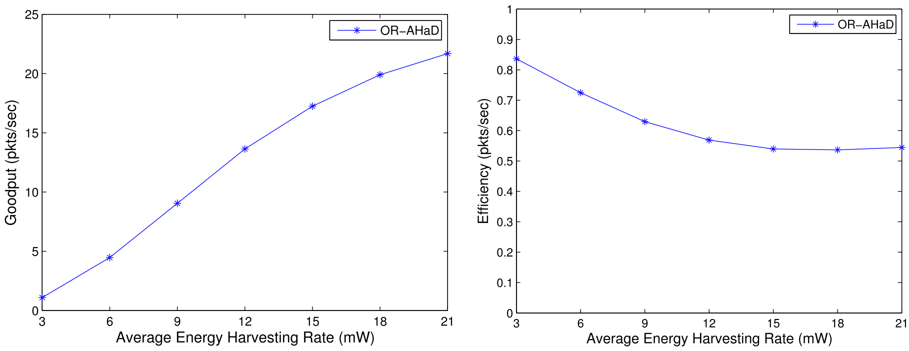


(c) Delivery Ratio

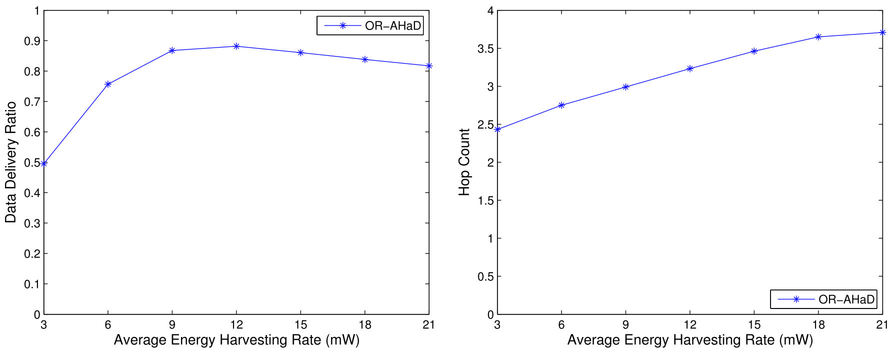
(d) HopCount

Figure 2.5 Performance results of varying γ (source deployed furthest from sink).

and as a result enhances goodput and delivery ratio. However, after some point, delivery ratio decreases slightly because of an excessive number of candidates. As for efficiency, it decreases because the increment in number of zones, scales-up the likelihood of duplicate reception. The increase in the likelihood of multi-path affects average hop count as well.



(a) Goodput (b) Efficiency



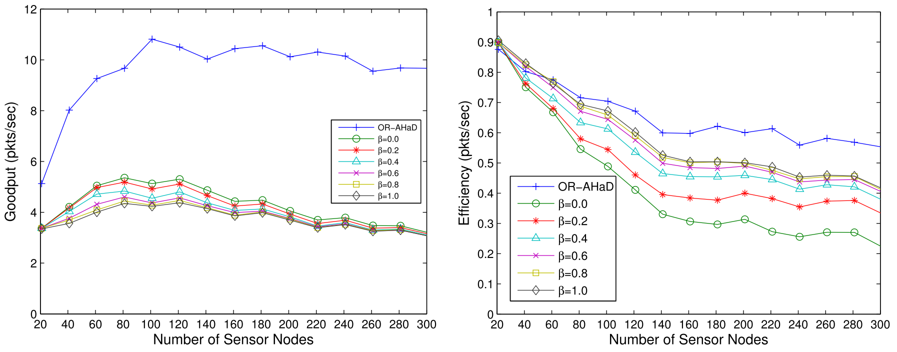
(c) Delivery Ratio (d) HopCount

Figure 2.6 Performance results of varying average harvesting rates.

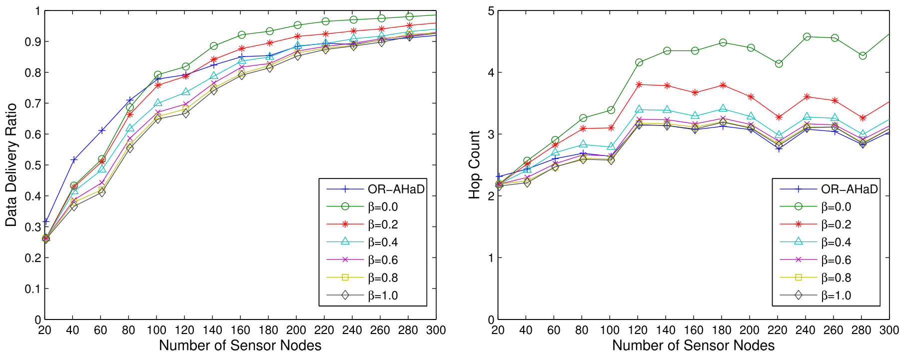
2.5.3 Comparing OR-AHaD with EHOR

To assess the performance gain of using adaptive harvesting-aware duty cycle management and combining coordination messages with geographical zoning, we compare our algorithm with EHOR. We consider different values of β which is the weighting factor for the transmission priority in EHOR [4]. We assume γ to be 1.0 in our algorithm for achieving the highest goodput.

We first assume a scenario where all the sensor nodes including the source are randomly deployed. The simulation results are as illustrated in Figure 2.7. In another scenario, the source node is deployed such that it is furthest way



(a) Goodput (b) Efficiency



(c) Delivery Ratio (d) HopCount

Figure 2.7 Comparing performance results of OR-AHaD with EHOR (source deployed randomly).

from the sink while the other sensor nodes are still deployed in a random way and the simulations are repeated. The performance results are presented in Figure 2.8.

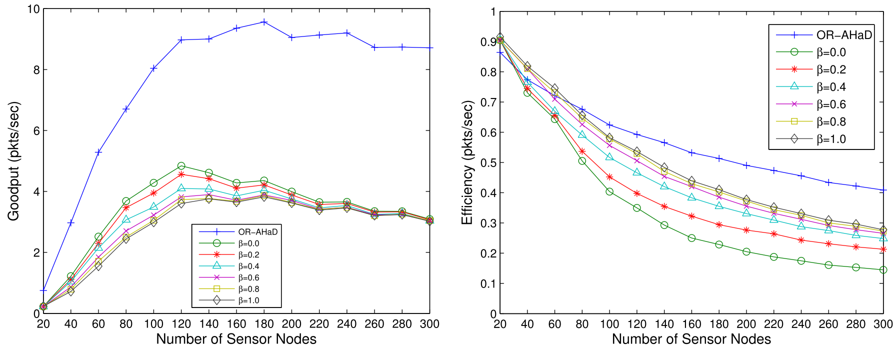
In both scenarios, OR-AHaD achieves much higher goodput in comparison to EHOR. Also, since the energy management model is based on the prediction of the future harvesting rate, a more suitable candidate set is available and active to contribute to forwarding the packets. The efficiency is also higher in OR-AHaD because the rate of duplicate packets is limited by using coordination messages. Even at the last hop, when the sink receives a data packet, it sends out coordination message like previous hops along the path. This way, all of the neighbor nodes are informed and prevented from relaying that data packet. But in EHOR when sink receives the data packet, it does not notify the neighbor nodes. This can affect efficiency especially when the number of nodes is relatively high. With delivery ratio, the reasoning is the same as goodput. However, after some point, delivery ratio in OR-AHaD becomes slightly less than EHOR . As mentioned before, the rate of sending new packets in OR-AHaD is higher in comparison to EHOR. Therefore, when we have a large candidate set because of the high number of deployed nodes, network load caused by multi-hop routing increases even more and hence, some packets may not make it to the sink. Hop count is almost the same in both algorithms.

2.6 Open Challenges

While a lot of efforts have been invested towards the design and adaptation of novel routing solutions for wireless sensor networks that take advantage of environmental energy to either supplement batteries or as the main source of power in the last few years, this research area is still relatively new, with an abundance of challenges that need to be investigated further. We dedicate this section to discussing some of these open challenges.

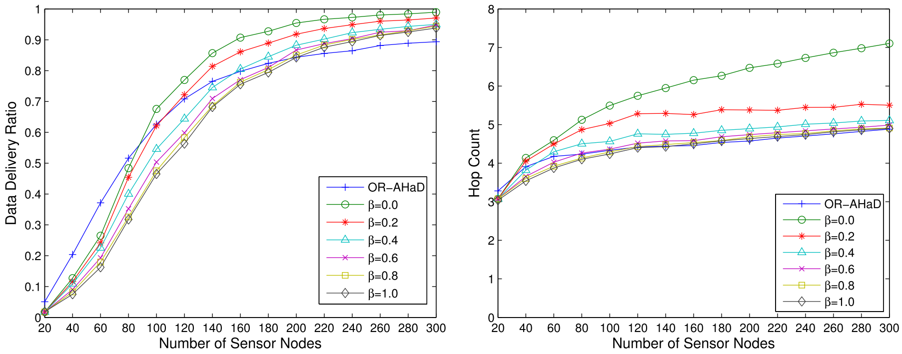
The core part of an energy harvesting sensor node is the harvesting system that scavenges energy from the environment [17]. The uncertainty and instability in energy availability that is inherent in ambient energy sources intensifies the role of harvesting models and prediction methods in the performance of routing algorithms. Therefore, it is essential to model energy harvesting and parametize the temporal, spatial and internal characteristics of harvesting devices, so that this can be exploited in routing decisions. On top of that, to increase the accuracy of forecasting, customized methods must be adopted for the specific type of harvesting device that is being utilized. While most of the existing methods concentrate on solar energy harvesting devices, less attention has been paid towards other types including thermal and vibrational (eg. [12, 14]). In addition, the effect of prediction accuracy in the performance of routing must be investigated extensively.

Some research activities have been conducted to evaluate routing algorithms in WSN-HEAP [5]. However, a unified evaluation framework is required to compare the existing solutions based on realistic MAC and physical layer specifications. This would give a heads up on the direction to be



(a) Goodput

(b) Efficiency



(c) Delivery Ratio

(d) HopCount

Figure 2.8 Comparing performance results of OR-AHaD with EHOR (source deployed furthest from sink).

taken for improving the performance of routing in WSN-HEAP. Theoretical bounds need to be derived for critical performance metrics such as goodput and delay to understand where the current solutions stand and how far they can progress. In addition to theoretical and simulation studies, existing routing algorithms should be testbedded to effectively take into consideration implementation issues, and to help realize the potential of WSN-HEAP in actual deployments.

Finally, possible security threats imposed by nature of the WSN-HEAP must be identified, from which preventive measures and solutions can be investigated and integrated with future routing and data dissemination solutions.

2.7 Conclusion

In this book chapter, we presented OR-AHaD, an Opportunistic Routing Algorithm with Adaptive Harvesting-aware Duty Cycling for WSN-HEAP. We proposed an energy management model which exploits the estimated value of harvesting rate in the near future and the residual energy to adjust the duty cycle of each node adaptively and integrated that in the opportunistic routing algorithm which prioritizes the candidates based on geographical information and by applying a zoning approach. Then, we introduced the use of coordination messages among candidates in a timer-based coordination method.

We evaluated OR-AHaD using extensive simulation. The results showed that goodput and efficiency is increased in comparison to EHOR, which is a previously proposed opportunistic routing scheme for WSN-HEAP. The proposed algorithm also performs well under different environmental energy harvesting rates. In the last section, we addressed the remaining open challenges in this area for future work.

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