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Upgrading Routing Functionalities in Asynchronous WSNs

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Abstract—Asynchronous sleep schedule and geographical routing are two efficient and scalable solutions for wireless sensor networks (WSNs). However, the schedule may degrade the delay performance of the routing protocol, and the optimal combined utilization of these two solutions is still an open question. In this letter, we propose a geographical-based opportunistic routing protocol for asynchronous WSNs. Each node maintains multiple relay candidates that make geographical progresses of more than a threshold γ, and opportunistically forwards data packet to the first candidate that wakes up. We can obtain the optimal end-to-end delay performance, by just tuning γ. Analytical and simulation results show that the derived optimal γ can make a good tradeoff between the single-hop delay and the hop count of forwarding path, and minimize the end-to-end delay of forwarding path.

Index Terms—Asynchronous sleep schedule, delay minimization, geographical routing, opportunistic forwarding.

I. Introduction

In wireless sensor networks (WSNs), nodes are typically powered by low capacity batteries but required to survive for long periods. It is well known that idle listening and overhearing of radio modules account for most of power consumption. In medium access control (MAC) layer, there have been various sleep schedule protocols that help reduce power consumption, by putting nodes into sleep mode when there is no data packet to send or receive.

These sleep schedule protocols can be classified roughly into two categories: synchronous and asynchronous. In the asynchronous protocols (e.g., [1], [2], [3]), nodes switch between sleep and active modes independently. Neighboring nodes establish rendezvous with each other only when there are some data packets to exchange. Without the periodical cost of time synchronization or schedule learning procedure, asynchronous protocols may achieve higher energy efficiency and better scalability than their counterparts. In this letter, we only focus on the asynchronous protocols. More detailed review results on sleep schedule protocols can be found in [4].

Geographical routing is another efficient and scalable solution in networking layer for WSNs. In geographical routing protocols, each node knows the geographical coordinates of itself, its neighbors, and the sink, and selects a neighbor that is closer to the sink than itself as the next-hop relay. Then, data packets can be forwarded to the sink hop by hop, with only local information. Early geographical routing protocols greedily select the neighbor with the maximal progress at each hop, to minimize the hop count of forwarding path and also the end-to-end delay. However, such a greedy strategy can no longer obtain the minimal delay performance in asynchronous WSNs, because the selected relay may wake up very late, incurring nontrivial waiting delay.

There have already been plenty of opportunistic routing protocols that are committed to reduce the waiting delay introduced by asynchronous sleep schedule and detailed review results can be found in [5]. The basic idea of opportunistic routing is that each node maintains multiple relay candidates that provide positive forwarding progresses to the sink, and dynamically forwards data packet to the first candidate that wakes up. Intuitively, the waiting delay can be reduced to $1/N$ times averagely, if there are N qualified relay candidates. However, without considering the geographical progress, opportunistic routing may suffer a very long forwarding path and an unacceptable end-to-end delay. Naveen and Kumar [6] minimized the single-hop waiting delay, subject to a constraint on the single-hop geographical progress. However, how to obtain the optimal end-to-end performance is not included. Kim *et al.* [7] tried to achieve the minimum average end-to-end delay, but at the expense of an initial complex configuration phase.

There are two recent works, [8] and [9], on opportunistic routing for asynchronous WSNs. In their models, duty-cycle is not low and plenty of candidates can wake up simultaneously to cope with the unreliable wireless transmissions. In this letter, we consider ultra-low duty-cycle WSNs, where only one candidate will wake up at each time with high probability. Gu and He [10] proposed an opportunistic forwarding protocol for low-duty-cycle and lossy WSNs, but they assumed a predetermined sleep schedule, which is not an absolutely asynchronous sleep schedule.

simulation results and section V concludes this letter finally.

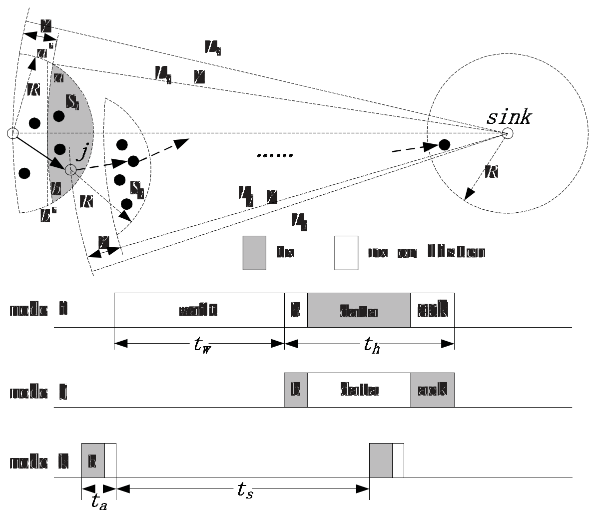

Fig. 1: Geographical Anycast in Asynchronous WSNs

II. SYSTEM MODEL AND PROBLEM FORMULATION

We assume that all nodes are uniformly distributed in a 2-D area, where the node density is δ. These nodes have the same radio communication radius R. All the data packets are triggered by very infrequent events, and need to be delivered to the unique sink as quickly as possible. Each node resorts to its neighbors that are closer to the sink to relay data packet ahead, if it can not reach the sink directly. We assume that each node knows the geographical coordinates of itself, its neighbors, and the sink, as in the existing geographical routing protocols.

Except that the sink always keeps active, the other ordinary nodes adopt the following asynchronous sleep/active schedule to save energy. When a node has no data packet to send, it alternates between active and sleep modes independently. Specifically, the active duration t_a is a fixed short period and the sleep duration t_s is an exponentially distributed random variable with mean value λ^{-1}. After switching to active mode, it first broadcasts a beacon to notify that it wakes up and then checks whether there is any incoming data packet from neighboring nodes. If not, it will go back to sleep when an active duration ends. Once holding a data packet to send, the node quits the above periodical schedule temporarily, keeps active and waits until a relay node wakes up to receive it. To reduce power consumption, we can set t_a to be exactly equal to the minimal duration that is needed by the above beacon notification and checking operation.

As shown above, the neighboring nodes only synchronize with each other when there are some data packets to exchange, and enjoy a low duty-cycle schedule most of the time. If network traffic is low enough, such an asynchronous schedule is very energy-efficient. However, the asynchronous schedule incurs additional waiting delay before forwarding data packet.

We use opportunistic forwarding to mitigate the negative impacts of asynchronous schedule on the delay performance. Specifically, each node selects the neighbors that make geographical progresses of more than γ (a parameter to be optimized) as its relay candidates, and dynamically forwards data packet to the candidate that wakes up first. A generic example of opportunistic forwarding is shown in Fig.1. Data packet generated by node i can arrive in the sink, through a multi-hop stochastic path $i, j, \ldots, sink$, which depends on the random sequence that relay candidates wake up. At the last hop, data packet can be forwarded to the sink directly, without incurring any additional waiting delay. It is obvious that the expected end-to-end delay only depends on γ when node density δ and sleep interval parameter λ are predetermined. In this letter, we will derive out the optimal γ to minimize the maximal source-to-sink delay.

Multiple beacons from different relay candidates may collide with each other. But this will not pose the serious impacts on the functionality of opportunistic routing. The only impact is that the sender will miss the affected candidates for this time and continue to wait for the subsequent candidates, increasing the waiting delay. Since the sender selects the first available candidate to relay packets, we mainly analyze the probability that the sender will miss the first candidate.

We denote the beacon duration by t_b, the number of neighbors N, the probability density function of sleep interval $f(\cdot)$. Without the loss of generality, we assume that the sender starts to wait at time 0 and the first beacon arrives at time x. If another beacon arrives between $[x, x + t_b]$, it will collide with the first beacon. This probability is given by $G(x) = \int_x^{x+t_b} f(y)dy$. On the other hand, the probability that another beacon will not collide with the first one is $H(x) = \int_{x+t_b}^{\infty} f(y)dy$. The probability that there are k different beacons collide with the first one is equal to $\binom{N-1}{k} G(x)^k H(x)^{N-k-1}$. Then, we can compute the probability that the sender will miss the first candidate by the following expression,

$$P_c = \binom{N}{1}\int_0^{\infty}\Big[\sum_{k=1}^{N-1}\binom{N-1}{k} G(x)^k H(x)^{N-k-1}\Big]\cdot f(x)dx. \quad (1)$$

We set the size of beacon as $15Bytes$, which is large enough to include *node id* and geographical information. With a typical data rate of $250kbps$, t_b can be expected to be less than $0.5ms$. The theory and simulation results of P_c are plotted in Fig. 2, where 10^6 tries were conducted for a particular pair of N and λ^{-1}. In general, the probability of missing the first candidate is very small. Even with the shortest sleep interval setting, ($\lambda^{-1} = 0.1$), P_c is still less than 13.5%. The probability that the first m candidates are all missed declines rapidly with the rise of m. To keep the paper concise, we omit such a tedious derivation. Thus, we can reasonably ignore the negative impacts of beacon collisions on opportunistic routing.

As in [7], we assume that all the data packets are triggered by very infrequent events and ignore the collisions among different traffic flows. Furthermore, we assume that all nodes have the same λ in this work and leave the sleep interval parameter optimization problem for our future work.

III. THE OPTIMAL GEOGRAPHICAL PROGRESS

Consider the case in Fig.1, and denote the distance between the source node i and the sink by L_i. The average number of

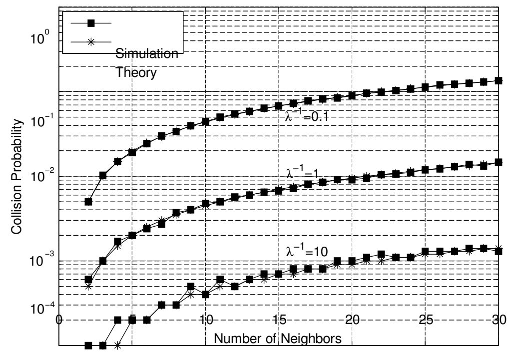

Fig. 2: The Collision Probability of the First Beacon

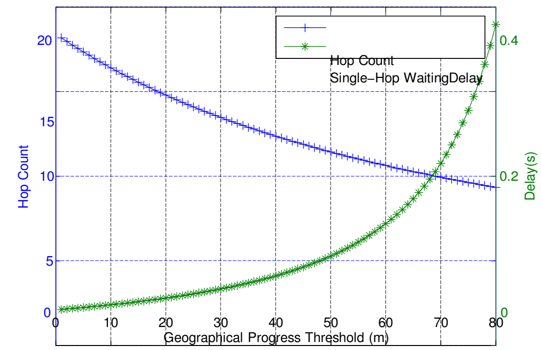

Fig. 3: Hop Count V.S. Single-Hop Waiting Delay ($\lambda^{-1} = 10s$)

relay candidates of node i (e.g., the nodes located within the grey region S_i) is given by $N_i = \delta A_i$, where A_i is the area of S_i and can be calculated by,

$$A_i(L_i,\gamma) = \int_\gamma^R 2(L_i - x)\arccos\left(\frac{L_i^2 + (L_i - x)^2 - R^2}{2L_i(L_i - x)}\right)dx, \tag{2}$$

which is a function of L_i and γ.

Since all candidates use the same sleep parameter, the probabilities that all candidates wake up first and become the relay node are the same. Then, the expected geographical progress from node i to the next-hop relay node can be expressed as

$$g(L_i,\gamma) = \int_\gamma^R \frac{2(L_i - x)\arccos\left(\frac{L_i^2+(L_i-x)^2-R^2}{2L_i(L_i-x)}\right)}{A_i} \cdot x \cdot dx. \tag{3}$$

Assume that node i starts to wait at time 0. The probability that one or more candidates wake up at time t is given by $N_i\lambda e^{-N_i\lambda t}$. Thus, the expected waiting time of node i before the first candidate wakes up can be calculated as

$$T_w(L_i,\gamma) = \int_0^\infty t \cdot N_i\lambda e^{-N_i\lambda t}dt = \frac{1}{\lambda N_i}. \tag{4}$$

Besides the waiting delay $T_w(L_i,\gamma)$, data packet undergoes additional transmission delay at each hop, i.e., the delay incurred by exchanging data packet and *ack* packet, which is denoted by t_h. Note that t_h mainly depends on the data packet length and wireless link quality. Then, the expected total delay of forwarding a data packet from a node whose distance to the sink is L can be calculated by the following recursive expression,

$$T(L,\gamma) = \begin{cases} T_w(L,\gamma) + t_h + T(L - g(L,\gamma),\gamma), & if L > R,\\ t_h, & otherwise. \end{cases} \tag{5}$$

We seek to minimize the expected total delay of forwarding a data packet from the farthest node to the sink.

$$\min_\gamma \quad T(L_m,\gamma) \qquad \text{s.t.} \quad 0 < \gamma \le R, \tag{6}$$

where L_m is the distance between the farthest node and the sink.

At the most hops of forwarding path, we can obtain $L_i >> R$ and use *string* $\acute{a}\acute{b}$ to approximate *arc ab*. So $A_i(L_i,\gamma)$ can be calculated by the following approximation expression,

$$\hat{A}(\gamma) = R^2 \arccos\frac{\gamma}{R} - \gamma\sqrt{R^2 - \gamma^2}. \tag{7}$$

and $g(L_i,\gamma)$ can also be estimated as,

$$\hat{g}(\gamma) = \int_\gamma^R x\frac{2\sqrt{R^2 - x^2}}{\hat{A}(\gamma)}dx = \frac{2(R^2 - \gamma^2)^{\frac{3}{2}}}{3\hat{A}(\gamma)}. \tag{8}$$

Note that both $\hat{A}(\gamma)$ and $\hat{g}(\gamma)$ are independent of L_i, meaning that there are the same number of candidates and the same geographical progress at all hops.

At the last hop, the average geographical progress from a one-hop-neighbor to the sink is equal to $\frac{\sqrt{2}}{2}R$. Then, $T(L_m,\gamma)$ can be estimated as

$$\hat{T}(L_m,\gamma) = \frac{(L_m - \frac{\sqrt{2}}{2}R)}{\hat{g}(\gamma)}\left(\frac{1}{\lambda\delta\hat{A}(\gamma)} + t_h\right) + t_h, \tag{9}$$

where the first summation part is the delay of forwarding a data packet from the farthest node to one-hop-neighbors, and equal to the product of hop count $\frac{(L_m - \frac{\sqrt{2}}{2}R)}{\hat{g}(\gamma)}$ and single-hop delay $\frac{1}{\lambda\delta\hat{A}(\gamma)} + t_h$. The last t_h is the delay from a one-hop-neighbor to the sink. We can derive out the optimal γ easily by summing up equations (6−9).

IV. Performance Evaluation

In this section, we evaluate the performance of the optimal opportunistic routing. Without loss of generality, 3000 ordinary nodes are uniformly distributed within a circular range, whose radius is $800m$, and the sink is located at center of this range. The communication range R is $100m$. 20 farthest nodes alternately generate 10^4 data packets in all. In order to avoid the contention of multiple data flows, the next data packet is triggered by the event that the previous one is delivered to the sink. We consider two kinds of scenarios, where t_h are $0.1s$ and $0.01s$, respectively. Sleep parameter λ^{-1} are set as $0.1s$, $1s$, and $10s$.

Fig. 3 shows how the hop count of forwarding path and the single-hop waiting delay vary along with geographical progress threshold γ, when λ^{-1} is equal to $10s$. γ only ranges

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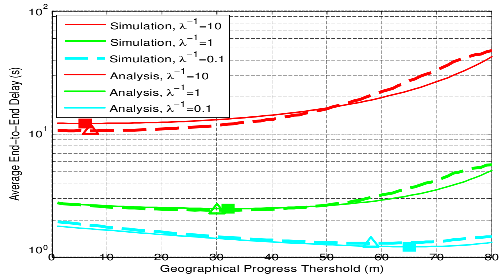
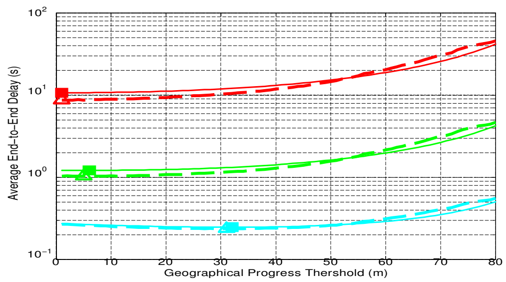


(a) $t_h = 0.1s$



(b) $t_h = 0.01s$

Fig. 4: End-to-End Delay

from 0 to 80 to avoid an empty relay candidate set. As γ increases, the hop count of path decreases while the waiting delay at each hop increases. So it is unknown which value minimizes the total end-to-end delay.

We present the end-to-end delay results in Fig. 4, where each point of the dashed curves indicates the average end-to-end delay of 10^4 data packets and the solid curves are the analysis results. The optimal values of simulation and theory results (e.g. the minimal end-to-end delay) are marked by triangle and square marks, respectively. We can see that the simulation results are very close to the theory results. In genearl, the larger λ^{-1} we set, the smaller the optimal γ is. When the average sleep intervals are long, we should permit relatively small geographical progress to reduce single-hop waiting delay, even this will extend the length of forwarding path. By comparing two sub-figures, it is easy to understand that small t_h results in smaller optimal γ under the same conditions.

In Fig. 5, we compare the end-to-end delay performance of the proposed protocol with the optimal anycast in [7]. For the sake of fairness, we also use the sender-initiated MAC of [7] in our protocol, and set $t_I = 6ms$. Each point on the curve is the average end-to-end delay of 10^4 data packets from 20 farthest nodes to the sink. We consider two different scenarios again, where $t_h = 0.01$ and $t_h = 0.1$. As shown in the figure, the delay performances of two solutions are nearly the same. The optimal anycast achieves slightly lower delay, but this weak advantage is at the cost of a very complex configuration phase. Similar comparison results can also be found in other scenarios with different node density settings. We omit these results to save space.

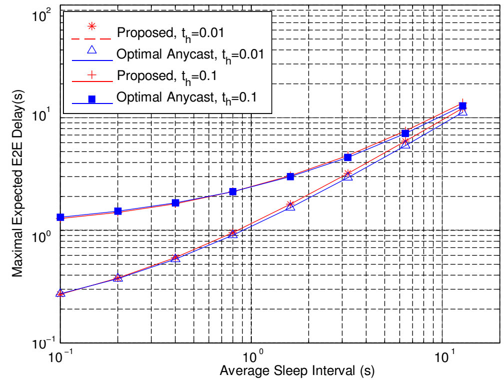


Fig. 5: Comparison with Optimal Anycast

V. Conclusion

In this letter, we optimized the geographical opportunistic routing for asynchronous wireless sensor networks, where all nodes go to sleep independently and the wake-up times of neighboring nodes are unknown. We achieved the optimal end-to-end delay performance by just tuning the geographical progress threshold. Due to the inherent load unbalance, the network consumes energy very unevenly. In our future work, we will try to mitigate the energy unbalance through optimizing the sleep schedule parameters.

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