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Modeling and analysis of opportunistic routing in low traffic scenarios

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Abstract

Opportunistic routing protocols have been proposed as efficient methods to exploit the high node densities in sensor networks to mitigate the effect of varying channel conditions and non-availability of nodes that power down periodically. They work by integrating the network and data link layers so that they can take a joint decision as to the next hop forwarding node based on its availability and suitability as a forwarder. This cross-layer integration makes it harder to optimize the protocol due to the dependencies among the different components of the protocol stack. In this paper, we provide a framework to model opportunistic routing that breaks up the functionality into three separate components and simplifies analysis. The framework is used to model two variants of opportunistic routing and is shown to match well with simulation results. In addition, using the model for performance analysis yields important guidelines for the future design of such protocols.

1. Introduction

Different opportunistic routing protocols have been proposed recently for routing in sensor networks [19, 20, 1, 4, 5]. Opportunistic routing is based on geographic routing which is predicated on every node being aware of its neighbors and their specific locations. In geographic routing, the network layer of a node selects a next hop forwarder to be the node that is furthest towards the destination. This information is then sent down to the MAC layer which waits till it can achieve rendezvous with the selected node. However, in sensor networks, availability of nodes can be disrupted significantly (due to channel fluctuations and duty cycling of nodes), hence the MAC layer may suffer a significant delay and energy overhead in retransmitting the packet till it can complete the transmission successfully.

Opportunistic routing extends the idea of geographic routing, by using some node that is awake and available for routing at the time the packet needs to be transmitted. The way it works is by integrating the network layer and MAC layers so that the network layer passes down a set of candidate forwarders and the MAC layer takes a final decision on the node to use depending on current connectivity. It still uses the node location information to inform this decision, however, the particular choice of forwarding node depends on the policies of the specific protocol variant. Obviously, this approach would be attractive in dense networks where the number of potential forwarders is large.

The concept of opportunistic routing is very powerful and well-suited to sensor networks where there are significant disruptions to node availability. However, there is a cost associated with the MAC layer trying to ascertain node connectivity at the time a packet needs to be transmitted, which may negate its advantages. In fact, the overhead can be expected to grow in dense networks (with high neighborhood cardinality) and might potentially be even higher than the cost incurred due to repeated transmissions in geographic routing.

Unfortunately, there has been very little work till now on providing analysis for this class of protocols with the exception of Zorzi and Rao ([19, 20]) who provide an analysis of the energy and latency performance of GeRaF. The analysis that they provide, however, is very specific to their protocol and does not provide insight into the performance of the general class of opportunistic schemes. Thus this paper attempts to understand the performance characteristics of these schemes, so that we can use that to optimize their operation and specify operational regimes (such as node densities, traffic rates etc.) when such protocols make sense.

Hence the first contribution of this paper is to present a modeling framework that can be used to analyze the different opportunistic routing schemes. The framework allows a very simple analysis of different opportunistic routing schemes since we decouple the opportunistic routing functionality into three pieces - routing, medium access and sleep discipline - which can be analyzed independently. That enables us to evaluate the performance of different mechanisms for each of the three components and then put them together for overall system performance. The metrics we use for performance comparison are power consumption at the nodes and average delay suffered by packets. This decoupling is based on an assumption of low traffic rates in the network (such that ≤ 1 packet needs to be forwarded in a neighborhood at any point in time) such as is envisioned in sensor networks. The applicability of the framework is presented in detail for region-based opportunistic routing, which was discussed in [4]. However, its generality is also demonstrated by modeling and analyzing GeRaF in brief.

The second contribution of this paper is to provide some fundamental guidelines for designing other opportunistic protocols so as to maximize performance. This is based on the analytical results obtained using the model. Specifically, we find the optimal shape for the forwarding region and show that the duty cycles of nodes should be extremely low such that ≤ 1 node is awake on average in the forwarding region (the exact value depends on various parameters).

The rest of the paper is organized as follows. Section 2 provides some background on the work in this area. This is followed by a description of the components of opportunistic routing in Section 3. The next three sections discuss each of the three components - routing, MAC and sleep discipline in detail. All these components are put together and the system performance for region-based opportunistic routing is shown in Section 7 where the analysis is also compared with simulation results. The applicability of the model to GeRaF is demonstrated in Section 8 followed by conclusions and future work in Section 9.

2. Related Work

Many variants of geographic routing protocols ([8, 7, 9]) have been proposed as efficient ways to scale with the number of nodes in the network. The distinguishing characteristic of this class of protocols is the use of node location information to route packets geographically towards the destination by forwarding to a neighbor that is located furthest towards the destination node. A number of recently proposed protocols fall under the category of *opportunistic routing protocols*. These protocols extend the concept of geographic routing by explicitly acknowledging the transient nature of the channel and node availability. The way they work is that the network layer specifies a set of potential next hop nodes while the data link layer decides the actual node to use based on the connectivity and priority of nodes within that set.

One example of opportunistic routing is region-based opportunistic routing ([4]) where the network layer specifies the set of nodes by defining a forwarding region in space that consists of the candidate nodes while the data link layer selects the first node available from that set to be the next hop node. A second example of opportunistic routing is [1] where the authors propose a protocol where the sender node transmits the packet with a specific priority of receivers specified in the packet. A system of slotted acknowledgements follows which informs all the nodes of the highest priority node that received the packet successfully. This node then forwards the packet ahead, while the other nodes drop the packet. Thus this scheme chooses the best placed node currently available. Yet another scheme that has been proposed is [3] where the idea of anycasting at the MAC layer is introduced which is similar in spirit to opportunistic routing. However, none of the above two works had detailed simulation results or analysis to show the efficacy of opportunistic routing.

One of the most detailed works in this area is GeRaF ([19, 20]) where the authors define a protocol that chooses the furthest node towards the destination among all the nodes that are closer to the destination than the current node. For this, they define sets of priority regions with nodes closest to the destination getting highest priority. Further, they define a fairly complicated handshake system to minimize collisions among nodes within a priority region. This will be shown later to be unnecessary since the network power consumption is minimized at extremely low wakeup rates for nodes, such that ≤ 1 node is awake on average for forwarding.

Opportunistic routing takes into account the duty cycling of nodes, hence another set of related works are topology management schemes. SPAN [2], STEM [13] and GAF [18] are all different approaches to that problem. SPAN identifies multiple sets of disjoint sets where each set provides connectivity to the whole network. On the other hand, STEM allows nodes to sleep periodically and uses beacons to rendezvous with the targeted node. Finally, GAF defines square grids where all nodes in neighboring grids can communicate with each other. All nodes within a grid are equivalent from routing purposes, hence nodes can share the routing load of the grid and sleep the rest of the time.

Multiple MAC rendezvous schemes have also been proposed in the literature. For e.g., [11] proposed two types of pseudo-asynchronous schemes - transmitter initiated (TICER) and receiver initiated (RICER). WiseMAC [6] is another interesting pseudo-asynchronous rendezvous scheme that uses the preamble sampling technique to rendezvous with nodes while trying to minimize the power consumption.

3. Opportunistic Routing Components

For analytical purposes, it is helpful to break down the opportunistic routing protocol stack into three components - routing, sleep discipline and medium access control (MAC). Typically, the routing component is part of the network layer while the sleep discipline and MAC components are part of the data link layer. Power control is another typical component of the data link layer, but we do not consider it here since we assume that the radio range of the nodes is fixed.

The routing component specifies the set of potential next hop nodes and how the forwarding node is to be chosen from that set. This set of nodes can be specified generally as a forwarding region in space that consists of nodes that can be used as next hop nodes for the current packet. Different variants of opportunistic routing specify different policies by defining different shapes and sizes of the forwarding region as well as different mechanisms for the selection of the forwarding node. Depending on the specification of the routing component, the average progress towards the destination is affected, which consequently affects the power and delay performance. Note that the actual choice of forwarding node is done at the data link layer of the node in opportunistic routing, but for analytical purposes, it is easier to consider it as part of the routing component of the framework.

The second component is the sleep discipline used. This refers to the mechanisms nodes use for duty cycling and to rendezvous with other nodes. Specifically, there are two mechanisms of particular interest. The first is the average time and distribution of the time nodes spend sleeping. For e.g., STEM [13] uses a fixed time between wakeups, while [16] describes a scheme where nodes sleep for exponentially distributed times. The second important part of the sleep discipline is the signaling mechanism nodes use when they have a packet to forward. For e.g., in TICER [11], nodes that have packets to forward transmit short RTS packets waiting for a receiver to respond, whereas in RICER [11], nodes that have packets to forward monitor the channel waiting for a potential receiver to send a beacon signaling that it is ready to forward a packet. These mechanisms determine the overhead imposed by the sleep discipline on the channel and energy consumption at the nodes.

Finally, the MAC component is concerned with how multiple nodes that need to access the medium at the same time contend for the channel and the process of contention resolution among them. This would occur when two or more nodes need to send a data or control packet at the same time, which could result in collision of the packets. To avoid that, multiple schemes have been proposed, such as CSMA-CA (carrier sense multiple access with collision avoidance), or the segmentation of nodes into priority regions in GeRaF so as to reduce the probability of collision among nodes. This component affects the probability of success of a packet and hence determines the number of times a packet needs to be retransmitted on average before it is forwarded successfully.

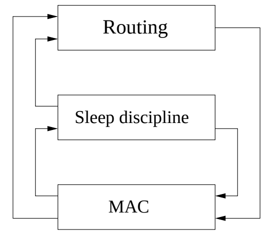

Figure 1. The dependencies among the typical components of the network and data link layers. Arrows from block A to block B show that block A affects the performance of block B.

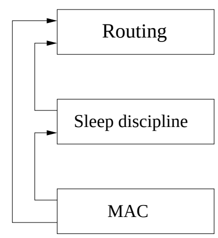

Figure 2. The dependencies among the typical components of the network and data link layers when the traffic in the network is very low. Arrows from block A to block B show that block A affects the performance of block B.

While we have divided the protocol functionality into these three components, typically each of these components influences the others creating dependency loops as shown in Fig. 1. As shown in the figure, the routing and sleep discipline components affect the MAC component since they affect network load in the form of data or control packets. The MAC component on the other hand affects the handshake between neighboring nodes, changing the performance of both the sleep discipline and the routing components. Finally, the sleep discipline component affects how two nodes rendezvous, changing the choice of forwarding nodes at the routing layer.

Thus this interdependency among components makes it very difficult to analyze an entire protocol stack, however, we can separate the components cleanly if we assume that the traffic is very low such that there is no cross traffic within an area. More specifically, if the average number of packets waiting to be transmitted within a neighborhood at any point in time is ≤ 1, we can separate the components since that means that packets from different nodes do not contend for the channel, removing the dependency of the MAC component on the routing and sleep components. The average number of packets within a neighborhood can be calculated using Little's Law (from queueing theory) as the product of the packet arrival rate (typically less than 1 packet/second/node for sensor networks) and the delay seen by each packet (shown later to be on the order of tens or hundreds of milliseconds). Hence under this assumption, the component dependencies are as shown in Fig. 2.

Within this analytical model framework, many different schemes can be considered for each of the three components. In the next three sections, we will consider each of the components illustrating how they can be modeled and the quantities of interest. We will also consider region-based opportunistic routing [4, 5] specifically, and analyze it in detail to illustrate the applicability of the model. We will proceed in a bottom-up fashion through the protocol stack, so that we can plug in the analysis of one component into the next as required by the dependencies in Fig. 2. Once the individual components are analyzed, they will be put together to understand the overall performance of the protocol.

There are two other assumptions we make to simplify the analytical treatment. The first is that we assume that the nodes are randomly distributed within the network, with a uniform distribution of parameter ρ and the second is that nodes are assumed to have circular radio ranges with all nodes having the same range R_{max}.

4. MAC component

The MAC component deals with avoiding collisions among multiple nodes that try to access the channel at the same time. In general, different nodes could have data packets to forward at the same time, potentially leading to collisions, however, under the low traffic assumption, the probability of that scenario is very low. On the other hand, multiple nodes may be active within a forwarding region, hence there may be collisions among the nodes during the process of choosing the next hop forwarder in opportunistic routing. This would affect the sleep discipline component as it changes the power cost of a rendezvous with another node and it affects the routing layer since it could change the choice of the next hop node. Hence the metric of interest for this component is the probability of success (i.e., the probability that the packet transmitted was successfully received) when there are N_{active} active forwarding nodes.

We can now analyze the specific case of region-based opportunistic routing. For this variant of opportunistic routing, collisions occur when multiple active forwarding nodes

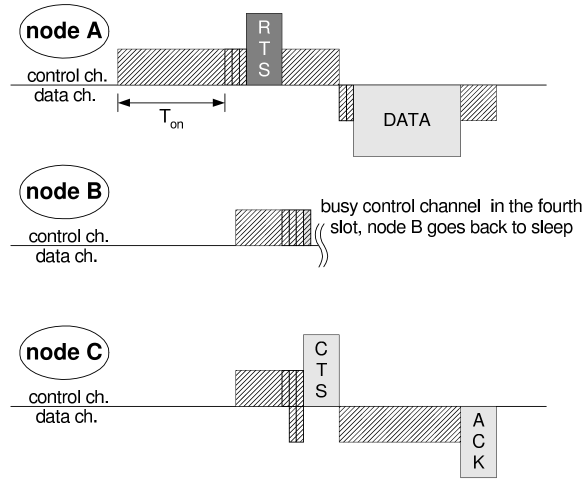

Figure 3. Rendezvous mechanism for nodes in region-based opportunistic routing

reply to an RTS beacon with a CTS packet. The reason multiple CTS packets are possible is because the RTS packet addresses all nodes within the forwarding region rather than a single node, thus all nodes that are awake at the time the RTS packet is sent will reply with a CTS.

Hence in region-based opportunistic routing, a short randomized, nonpersistent CSMA is introduced to avoid collisions between replying nodes. All nodes in the forwarding region that receive the RTS beacon sense the channel for a random number of sensing slots (maximum of M slots). The CTS is only sent out in case the medium was idle for the whole sensing duration. If nodes detect the channel to be busy, they suppress their own CTS as they assume that another node transmitted a CTS already. Therefore the sending node has to wait for the maximum sensing time + one CTS duration between two consecutive RTSs. The MAC mechanism is illustrated in Figure 3 for one sending node with two nodes awake in the forwarding region. We can analyze the probability of success for this contention resolution scheme when N_{active} nodes are awake in the forwarding region and the number of sensing slots is M as,

$$Pr\{\text{success}|N_{active} \text{ active nodes, M sensing slots}\} = \sum_{i=1}^{M} \binom{N_{active}}{1} \left(\frac{1}{M}\right) \left(1 - \frac{i}{M}\right)^{N_{active}-1} \quad (1)$$

This is because nodes sense the channel for a random number of sensing slots before sending a CTS. Hence a successful CTS transmission occurs if there is no collision during

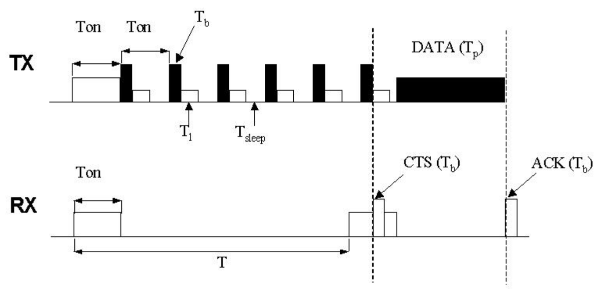

Figure 4. TICER rendezvous mechanism

the slot when the first node (among all the active nodes) tries to send a CTS.

5. Sleep discipline component

Sleep discipline refers to the mechanism nodes use to duty cycle so as to conserve energy. Hence this affects the availability of nodes as forwarders for data packets. As mentioned in the section on related work, many different duty cycling schemes have been proposed for sensor networks. For the purposes of modeling opportunistic routing, however, we are only concerned with two quantities. The first is the average cycle time of the nodes. The second quantity is concerned with the energy used during rendezvous between nodes before a data packet can be forwarded. This can then be used to calculate the average energy required to transmit a data packet as well as the latency involved per hop. In conjunction with the routing component, we can then calculate the network-wide power consumption and end-to-end latency.

Let us now consider the specific case of the region-based opportunistic sleep discipline protocol which is a variant of the TICER (Transmitter Initiated CyclEd Receiver) protocol described in [11]. In TICER, nodes are duty cycled so as to minimize power consumption. Packet transfer between two duty cycling nodes is achieved by sending a series of beacons till the nodes rendezvous. This is illustrated in Fig. 4. The opportunistic data link layer augments TICER using the MAC mechanism described in the previous section so that it can handle multiple nodes in forwarding regions rather than just single nodes as forwarders.

As shown in Fig. 4, nodes have a sleep/wake cycle of period T. On waking up, a node listens to the channel for T_{on} seconds to see if it can forward a packet. When a node has a packet to send, it sends an RTS packet specifying the forwarding region, then waits for a CTS reply. The RTS packets are sent every T_{on} seconds. On successful reception of a CTS packet (which is sent following the MAC mechanism described in the previous section), the node forwards the data packet to the node in the forwarding region which sent the CTS and waits for an ACK to confirm that the packet was received successfully. Packet arrivals are assumed to be random, hence when a node receives a packet, every node in the forwarding region has to wake up within T seconds, however, the exact time they wake up is uniform randomly distributed within T. Also, we can consider the entire cycle time of T to be divided into T/T_{on} number of *slots* (which is distinct from the M sensing slots of the MAC component) of length T_{on} and hence we need to find the average number of slots before a rendezvous between the sender node and a forwarding node occurs.

There is another factor that also affects the probability of successful transmission of a packet. This is the factor corresponding to the channel quality. Since traffic is very rare, we can assume that the channel quality is uncorrelated for different packets, and the probability of a successful transmission is given by p_{ch}. Also since the packets are relatively short, we can assume that the channel remains relatively constant for the entire handshake. Thus once the RTS packet goes through, we can assume that the rest of the transaction is successful.

Let the number of nodes in the forwarding region be N_{fwd}. Then we can calculate the probability of successful rendezvous as,

$$p \approx p_{ch} \sum_{k=1}^{N_{fwd}} \binom{N_{fwd}}{k} \left(\frac{T_{on}}{T}\right)^k \left(1 - \frac{T_{on}}{T}\right)^{N_{fwd}-k} \cdot Pr\{\text{success}|k \text{ active nodes, M sensing slots}\} \quad (2)$$

Hence approximating the wait time as a geometric distribution, the average number of slots before we get a successful rendezvous is,

$$E[slots] = \frac{1}{p} \quad (3)$$

Note that for the actual region-based opportunistic routing protocol, a rendezvous with some forwarding node occurs w.p. 1 (unless CTS collisions take place or the channel is bad) within time T, but this is not captured by the geometric model (though the probability is pretty close to 1 for the model also). So if we denote the wakeup rate of a node by $\mu = 1/T$, then the power consumption at a node is given by,

$$E[\text{power}] = \mu E_{wakeup} + P_{sleep} + \lambda(E[slots]E_{beacon} + E_{data} + E_{ack}) \quad (4)$$

Here E_{wakeup} is the energy spent on listening for time T_{on} when the node wakes up and P_{sleep} is the power consumption when the node is powered down. E_{beacon} is the energy spent on sending the RTS beacons and waiting for the CTS

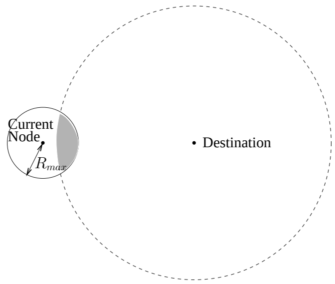

Figure 5. Lens shape as forwarding region

replies while E_{data} and E_{ack} is the energy required to transmit and receive the data and ACK packets. The packet arrival rate at a node is given by λ which can be calculated as shown in Section 6. The delay suffered by a packet can be calculated similarly. Denoting the time required to transmit the data and ACK packet by T_{data} and T_{ack} respectively, the per-hop delay is given by,

$$E[\text{per-hop delay}] = E[slots]T_{on} + T_{data} + T_{ack} \quad (5)$$

6. Routing Component

As mentioned before, the routing component is concerned with the specification of the forwarding region and how the next hop forwarding node is chosen. We assume that the forwarding region is a shape defined in space and all nodes within that region are potential forwarding nodes. Thus for the routing component, the progress made per hop would determine the overall power and delay performance of the protocol.

6.1. Optimal forwarding region

Let us first find the optimal shape of the forwarding region. Now the area of the forwarding region affects the number of nodes that may be candidate forwarders, and consequently the probability that at least one of them of is awake and can transmit the packet. If we now choose a region of area A as the forwarding region then the maximum progress is provided when the shape of the region is a lens (Fig. 5) formed by the radio range of the current node and the circle centered at the destination (with the radius such that the area under the lens is A). This is intuitive since we are using the region of the radio range circle which is closest to the destination node. Moreover, we can generalize the concept of a lens when the radio range is not circular to the region that is more than a certain distance away from the current node towards the destination.

We can now compute the average distance moved per hop for opportunistic routing. We will consider the case

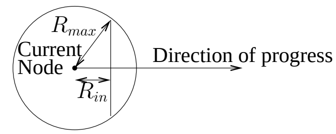

Figure 6. Calculation of progress

of the best node being used for forwarding. By best node, we mean the node furthest towards the destination that is available for routing at the time the packet needs to be forwarded. To make the calculations simpler, we assume that the destination is infinitely far away from the current node. Hence the lens reduces to a segment of a circle with inner radius R_{in} as shown in Fig. 6.

Now, the average distance moved towards the destination per hop when the best neighbor is used can be computed by following a similar derivation as [14]. If the progress is d, then $Pr\{d \leq x\} = e^{-\rho\phi q(x)}$ where ϕ is the duty cycle of the node and $q(x)$ is the area of a segment of a circle where the chord is at a distance x from the center. Obviously, $N_{active} = \rho\phi q(R_{in})$. Hence the average progress per hop is given by,

$$E[\text{progress}] = \int_{R_{in}}^{R_{max}} x \cdot Pr\{x < d \leq x + dx\}$$
$$= R_{max} - R_{in} e^{-\rho\phi q(R_{in})} - \int_{R_{in}}^{R_{max}} e^{-\rho\phi q(x)} dx \quad (6)$$

Note that,

$$q(x) = R_{max}^2 \arccos\left(\frac{x}{R_{max}}\right) - x\sqrt{R_{max}^2 - x^2} \quad (7)$$

To find the optimal value of R_{in}, we can differentiate Eqn. 6 (using Liebniz's rule) and equate it to 0. That calculation shows the optimal value of the inner radius R_{in} to be 0. In other words, the network layer should use any node that is closer to the destination for forwarding packets so as to maximize the average progress per hop.

6.2. Optimal number of active forwarders

We can now find the optimal number of active forwarders (in other words, the optimal value of ϕ) that minimizes the power consumption. If we ignore the sleeping power (which is usually negligible since that is just the leakage power and some power to maintain memory and node state), Eqn. 4 becomes:

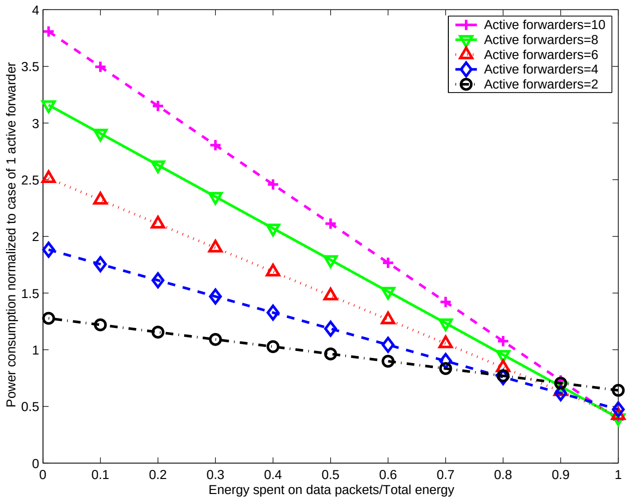

Figure 7. Normalized power consumption in the network for different number of active forwarders as the ratio of power spent on forwarding packets to the total energy consumption changes. The power consumption is normalized to the baseline case of having only one active forwarder.

$$P_{total} = \underbrace{\mu E_{wakeup}}_{\text{Wakeup power}} + \underbrace{\lambda \left(E[slots]E_{beacon} + E_{data} + E_{ack}\right)}_{\text{Data power}} \quad (8)$$

Let us now define the baseline to be the case when the duty cycle ϕ is such that there is exactly 1 node awake on average within the forwarding region ($N_{active} = 1$). We can then find the conditions under which it is suitable to have multiple nodes awake in the forwarding region. Note that when $N_{active} \geq 1$, $E[slots] = 1$ because at least one node is available for forwarding at any time. Also, define κ to be the fraction of power spent on forwarding packets (data power) to the total power consumption for the baseline case of $N_{active} = 1$.

$$\kappa = \frac{\lambda \left(E_{beacon} + E_{data} + E_{ack}\right)}{P_{total}}$$

We can plot P_{total} when we have different number of active forwarders and normalize to the baseline case as the value of κ changes. This is shown in Fig. 7. As can be seen, as the ratio of energy spent on data packets increases, it becomes profitable to move to multiple active forwarding nodes. Specifically, when the amount of energy spent on data packets exceeds 60%, the transition from 1 to 2 active forwarders takes place. However, it is very unlikely that the amount of energy spent on data packets is more than the wakeup energy. For one, the wakeup rate is usually larger than the packet arrival rate in such networks ([19, 5]). Secondly, the amount of energy spent on one wakeup is comparable to the energy spent on transmitting one data packet.

Till now we have considered the general case of opportunistic routing. Let us now consider and analyze the specific case of region-based opportunistic routing. In that case,

$$\begin{aligned} \kappa &\geq 0.6 \\ \Rightarrow \lambda &\geq \frac{0.6}{0.4} \cdot \frac{E_{wakeup}}{E_{beacon} + E_{data} + E_{ack}} \cdot \mu \\ &= 1.5 \times \frac{E_{wakeup}}{E_{beacon} + E_{data} + E_{ack}} \cdot \frac{1}{N_{fwd} T_{on}} \end{aligned}$$

Note that when $N_{active} = 1$, $\mu = 1/(N_{fwd} T_{on})$. Now, since the channel in a neighborhood cannot be occupied more than 100% of the time, $\lambda N(T_{on} + T_{data} + T_{ack}) \leq 1$. The occupancy of the channel is calculated by the product of the total number of packets in a neighborhood and the time each packet and its overhead occupies the channel. Hence, we require,

$$1.5 \times \frac{N}{N_{fwd}} \cdot \frac{T_{on} + T_{data} + T_{ack}}{T_{on}} \cdot \frac{E_{wakeup}}{E_{beacon} + E_{data} + E_{ack}} \leq 1 \quad (9)$$

Now, $N_{fwd} = 0.4N$ when the destination is infinitely far off. Also, assuming that the power spent for transmitting and receiving is the same and that all control packets (RTS, CTS and ack) have the same length, we get,

$$\begin{aligned} 3.75 \times \frac{4T_{control} + T_{data}}{3T_{control}} \cdot \frac{3T_{control}}{4T_{control} + 2T_{data}} &\leq 1 \\ 3.75 \times \frac{4T_{control} + T_{data}}{4T_{control} + 2T_{data}} &\leq 1 \end{aligned}$$

which is not possible for any positive values of T_{data} and $T_{control}$. Hence, for the specific case of region-based opportunistic routing, it is always more efficient to have just 1 active forwarder in a forwarding region.

6.3. Calculating traffic rate (λ)

Since we have determined that the optimal forwarding region is a lens with inner radius $R_{in} = 0$ and that only one node should be active at any time, it reduces to choosing a node at random for forwarding. Note that this is exactly what the region-based opportunistic MAC protocol does, since the first node that responds to an RTS beacon is chosen for forwarding, which effectively means that the choice of node is random. Hence for a random choice of node, if we know that there is at least one node present within the forwarding region, then the average distance moved towards the destination is given by,

$$
\begin{aligned}
& E[\text{progress}|\text{at least one node in the forwarding region}] \\
&= \int_{R_{in}}^{R_{max}} x \cdot Pr\{\text{progress is x}\} \cdot dx \\
&= \int_{R_{in}}^{R_{max}} x \cdot \frac{2\sqrt{R_{max}^2 - x^2}}{q(R_{in})} \cdot dx \\
&= \frac{2(R_{max}^2 - R_{in}^2)^{3/2}}{3q(R_{in})} \qquad (10)
\end{aligned}
$$

Using this, we get the average amount of progress per hop (for $R_{in} = 0$ and $R_{max} = 10$ meters) to be 4.24 meters. We can use this to calculate the average number of hops that a packet must traverse and consequently the average amount of traffic per node seen in the network. This is given by,

$$\lambda = \frac{\text{Traffic generation rate} \times \text{Avg. number of hops}}{\text{Number of nodes}} \qquad (11)$$

7. System Performance of region-based opportunistic routing

We can now put together the various components discussed in the previous sections to obtain the power and delay performance of region-based opportunistic routing as a whole. To verify the correctness of the analysis, we also conducted simulations for the region-based opportunistic routing protocol and the analytical results are compared.

7.1. Simulation Setup

The simulation study was carried out using the discrete event simulator OMNeT++ [17] enhanced by the TKN Wireless Framework [15]. Varying number of nodes were randomly placed in a $50m \times 50m$ grid. Poisson distributed traffic was generated at 8 nodes on the edge of the network with destinations being the opposite edges of the grid such that the amount of traffic seen at all points in the network is about the same. Traffic was generated at the source nodes at a rate of 1 packet every 10 seconds. In addition, a circular radio range model was assumed, while the interference range was about 1.5 times the radio range (the interference vs. radio range depended on the radio parameters in [12]). We use a two channel solution - data (only for data packets) and control (for control packets such as RTS, CTS and ACK packets) channel - so as to minimize collisions.

Finally, the bit error model in [10] is mapped to a packet error model. Since [10] showed that the run length distribution of bit errors is heavy-tailed, a Pareto distribution can be used to approximate the distribution and to obtain bit errors in a packet. Hence the shape parameter α of the Pareto distribution determines the quality of the channel with higher values of α signifying worsening channels. Various simulation parameters are specified in Table 1.

Table 1. Simulation Parameters

Geographic RTS, CTS, ACK	72 bits
Opportunistic RTS	88 bits
MAC service data unit (MSDU)	200 bits
Bit rate	40 kbps
$f_{carrier}$	1.9 GHz
Receiver Sensitivity	-80 dBm
P_{sleep}	40μW
$P_{receive}$	2.5 mW
$P_{transmit}$	4.5 mW
$P_{rx\_tx\_turnaround}$	2 mW
Radiated power	1 mW
$\alpha_{pathloss}$	3.5
Radio range	10 meters

7.2. Simulation Results

Fig. 8 shows the power consumption as the wakeup rate per node (μ) is changed. Since packets were generated at edge nodes at the rate of a packet every 10 seconds, that meant that the forwarding load was 0.093 and 0.062 packets/second/node for the two cases of 8.8 and 16.3 neighbors/node respectively. Both the simulation results and the theoretical results (Eqn. 4) are compared in the figure. Additionally, the per-hop delay is shown in Fig. 9 where the theoretical results of Eqn. 5 is compared with the simulation results for the two different node densities.

Fig. 8 also shows a very interesting result. From the figure, we can clearly see that the wakeup rate per node that minimizes the power consumption is 3.3 wakeups/second for the case of 8.8 neighbors/node. This corresponds to a node having a duty cycle of only 1.6%, or $N_{active} = 0.056$ nodes. Moreover, Fig. 10 shows the optimal value of N_{active} as the value of λ is changed. As can be seen, $N_{active} < 1$ for all the cases. This has also been observed using simulations in [5]. Hence, the actual number of active forwarding nodes should be *lower* than 1 in many cases to minimize the power consumption. This result is not at odds with the result in the analysis of the routing component

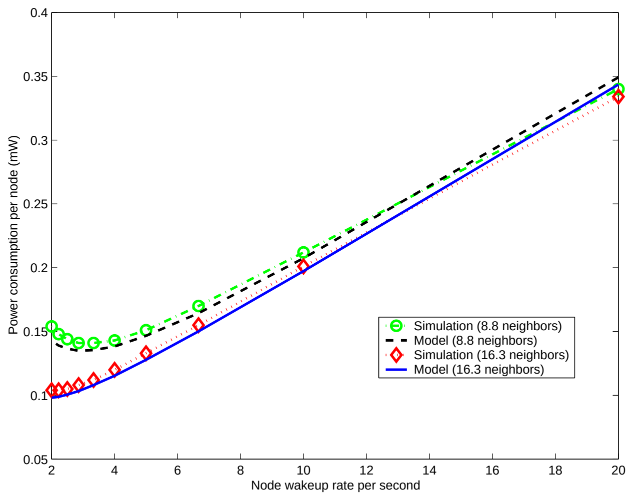

Figure 8. Comparison of theoretical and simulated power consumption per node as the wakeup rate per node is changed

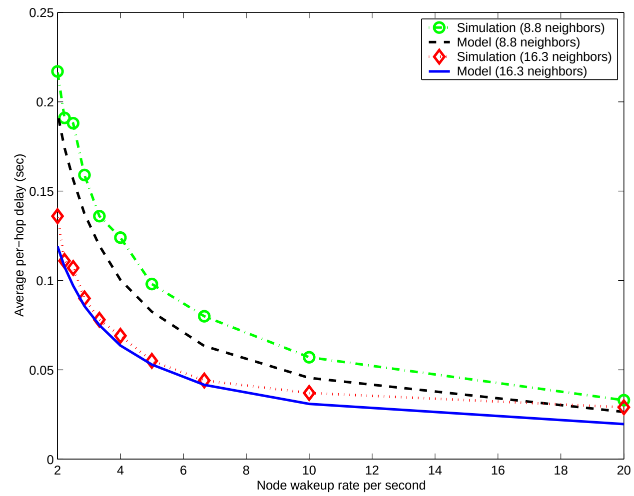

Figure 9. Comparison of theoretical and simulated per-hop delay as the wakeup rate per node is changed.

since the analysis only considered values of $N_{active} \geq 1$ for which $E[slots] = 1$.

For the case of $N_{active} < 1$, the sending node has to wait for a while before a node in the forwarding region wakes up and forwards the packet ($E[slots] > 1$). However, the value of λ remains the same as for $N_{active} = 1$ as the progress per hop is the same. Hence, the tradeoff here is between lowering the wakeup rate so as to save the wakeup power on one hand and on the other hand increasing the data power by making a node wait too long before it can finally rendezvous with a forwarding node. This clearly shows that in most cases in sensor networks, the energy spent on wakeups is usually larger than the energy spent on forwarding data packets, and consequently $N_{active} \leq 1$.

We can also check if our assumption of no cross-traffic in a neighborhood is valid. This can be done by figuring out the average queue size within a neighborhood (number of packets waiting to be forwarded within a neighborhood), which ≤ 1. This is shown in Fig. 11 for the case of 8.8 neighbors/node. The plot is generated for different traffic rates at a node by figuring out the per-hop delay for a packet corresponding to the wakeup rate that minimizes the power consumption and multiplying this delay by the traffic arrival rate. By Little's law, this is the average queue size within a neighborhood.

8. Modeling GeRaF

We can also use our framework to model other opportunistic routing protocols. This is done in the following for the GeRaF protocol described in [19, 20]. Their protocol is similar in nature but a bit more complicated than region-based opportunistic routing. The complications come from the fact that they try to choose the best node available towards the destination and carefully resolve any collisions among nodes that arise. However, as shown in Section 6, ≤ 1 nodes would be awake on average within the forwarding region for minimal power consumption, hence for modeling purposes we can still consider the choice of node to be random. In that case, we only need to model the sleep discipline and MAC components.

Since the number of nodes in the forwarding region is given by N_{fwd}, the number of failed attempts to reach a forwarding node is given by $(e^{N_{fwd}} - 1)^{-1}$. Also since the choice of node is random, we can assume that the forwarding node is equally likely within the N_p priority regions that is defined in the protocol (we'll take $N_p = 4$ as in [19]). Hence, if E_{RTS} and E_{CTS} is the energy required for sending the RTS and CTS packets respectively, the power consumption per node is given by,

$$E[power] = P_{wakeup} + P_{sleep} + \lambda\Big\{(e^{N_{fwd}} - 1)^{-1} N_p E_{RTS} + \frac{N_p}{2} E_{RTS} + E_{CTS} + E_{data} + Eack\Big\} \quad (12)$$

Fig. 12 plots the power consumption per node using the above equation and Eqn. 15 of [19] for two different node densities and packet arrival rates per node (λ). The channel was assumed to be perfect so that there was no packet loss due to bit error, so as to match the analysis in [19]. As can be seen, the simple analysis given above matches their results fairly well. Moreover, note that the optimal wakeup

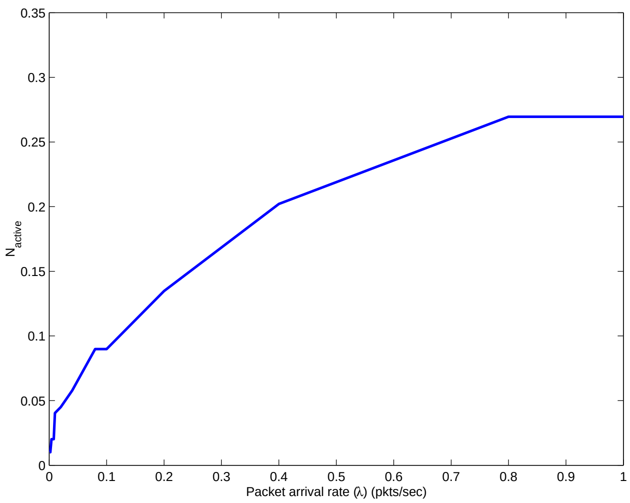

Figure 10. Optimal number of active nodes in the forwarding region as the traffic rate is changed.

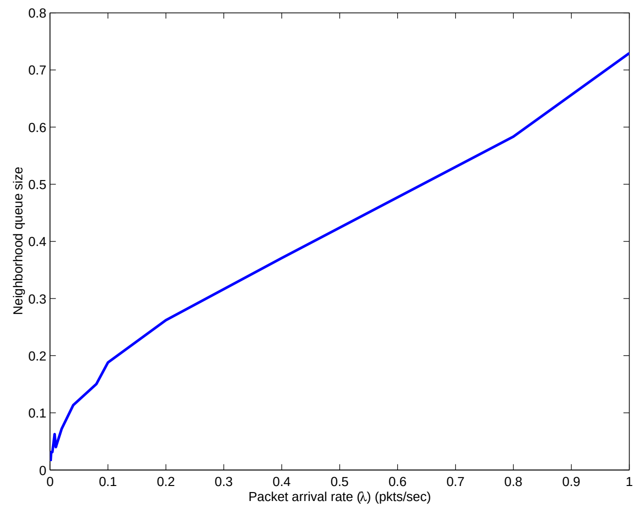

Figure 11. Average number of packets waiting to be forwarded within a neighborhood corresponding to the wakeup rate that achieves minimum power as the traffic rate is changed.

rate for GeRaF is also fairly low such that only $0.02 - 0.2$ nodes are awake in the forwarding region on average, which is as expected. This shows that for such low traffic rates, the simple modeling framework introduced in this paper models different variants of opportunistic routing accurately.

9. Conclusions and Future Work

This paper presented a framework for modeling opportunistic routing protocols. The framework is only valid for low traffic networks since it assumes that there is no cross-traffic at any node. Using that assumption, it separates out the routing, sleep discipline and medium access components to allow easy analysis. This is extremely useful as it enables different mechanisms to be plugged in for each of the three components and using that to analyze overall system performance. This was demonstrated in detail for region-based opportunistic routing and for GeRaF in brief.

A very useful design guideline that came out of this modeling was the fact that to minimize power consumption it is best to have ≤ 1 node awake within the forwarding region. The optimal forwarding region was also shown to be the lens formed by the radio range of the current node and the circle centered at the destination with radius equal to the distance between the current node and the destination.

The next step is to use the performance results obtained by the analysis to understand the trade-off between the power consumption and the latency suffered by the packets. This would help in evaluating the trade-off between network lifetime and the latencies allowed by the application. One thing to note is that the optimal wakeup rate is dependent on the traffic rate, however, it is not easy for a node to estimate the traffic in its neighborhood when it is asleep for most of the time. Hence a mechanism needs to be developed which would allow a node to accurately estimate the traffic and adjust its wakeup rate accordingly. Adding that mechanism to opportunistic routing would be essential in deploying such a protocol and ultimately extending the lifetime of energy-constrained sensor networks.

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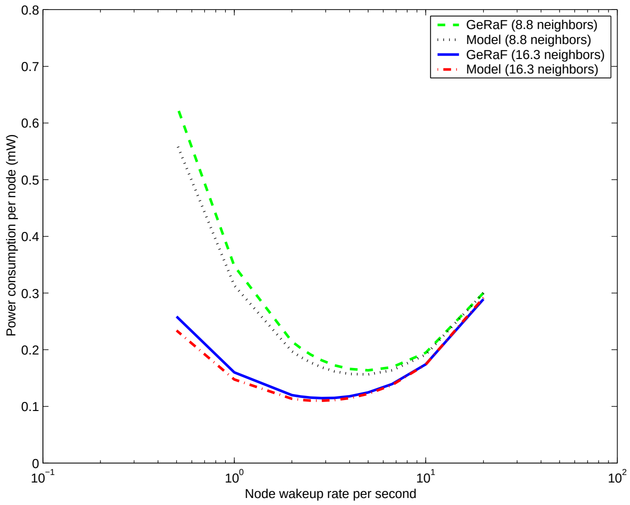

Figure 12. Comparison of the analytical model and Eqn. 15 of [19] for the power consumption per node as the wakeup rate is changed.

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