Hierarchical Power Management in Disruption Tolerant Networks with Traffic-Aware Optimization

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ABSTRACT

Disruption tolerant networks (DTNs) are wireless mobile networks that are characterized by frequent partitions and long delays. Such networks can be used in highly-challenged environment in which energy resources are limited. Efficient power management, therefore, is essential for their success. In this paper, we present a hierarchical power management in DTNs where nodes are equipped with two complementary radios: a long-range, high power radio and a short range, low-power radio. In this architecture, energy can be conserved by using the low-power radio to discover communication opportunities with other nodes and then wake up the high-power radio to undertake the data transmission. We develop a generalized power management framework and its variations around this idea and evaluate their relative performance. In addition, for the case in which traffic load can be predicted, we devise approximation algorithms to control the sleep/wake-up cycling to provide maximum energy conservation while discovering enough communication opportunities to handle a given traffic load. We evaluate our schemes and our choice of parameters through ns-2 simulations. Our simulation results show that the generalized power management mechanism could augment the usefulness of the low power radio and achieve better energy efficiency than mechanisms relying on one radio for discovery. In addition, our approximation algorithms reduce energy consumption from 73% to 93% compared with the case without power management. We also observe that while an additional low power radio does reduce the energy consumption needed for discovery, the improvement could be negligible in mobile DTNs due to the low density of nodes.

1. INTRODUCTION

Network designers often think of mobility as a detriment to building robust networks. However, recent efforts in Disruption Tolerant Networks (DTNs) have shown that mobility can be a powerful means for delivering messages in highly-challenged environments [10, 14, 24, 13, 35, 16, 6]. DTNs are wireless mobile networks that are particularly useful in sparse environments where the density of nodes is insufficient to support direct end-to-end communication. When mobile nodes encounter each other, opportunistically or intentionally, they pass messages to route them toward their final destinations. Unfortunately, many mobility scenarios depend on untethered devices with limited energy supplies. Without careful management, therefore, depleted energy supplies will degrade network connectivity and counteract the robustness gained by mobility.

While energy savings is necessary, mobile devices exhibit a tension between saving energy and providing connectivity through opportunistic encounters. In order to pass messages from node to node, the device must discover other nodes—typically the discovery is done using the same wireless interface used for message transfer. At the same time, energy savings necessitates disabling (i.e., sleeping) the wireless device—the wireless interface is one of the largest energy consumers in mobile devices [20] whether they are actively communicating or just listening ([11, 29]). If the wireless interface is asleep, the node cannot discover other nodes for communication and other nodes cannot discover it, either. The time periods when two nodes can communicate with each other are called *contacts* [14]. When networks are partitioned most of the time, it is not trivial to discover contacts while also saving energy. Therefore, designing power management for DTNs in this way is challenging since a node needs to detect when it can communicate with other nodes while aggressively disabling its radio during the remaining periods.

In previous study, we have shown how nodes can effectively use statistical information about network connectivity to predict when to enable their wireless interfaces and search for contacts [18]. However, such prediction could save considerable amount of energy only when the network connectivity has a certain degree of regularity. Thus, a network with significant randomness in node mobility requires better mechanisms to save energy while delivering messages.

In this paper, we examine the possibility of using a hierarchical radio architecture in mobile DTNs, in which nodes are equipped with two complementary radios: a long-range, high-power radio and a short-range, low-power radio. In this architecture, energy can be conserved by using the low-power radio to discover contacts with other nodes and then wake up the high-power radio to undertake the data transmission. Previous studies using this hierarchical radio architecture have considered only densely deployed networks, in which the short range of the low power radio is sufficient to discover each other [25, 28, 21]. However, a node in DTNs is often far away from the rest of the network. Therefore, if a node relies only on the low power radio to discover contacts, it may miss them due to the shorter range. To avoid missing too many contacts, we propose a generalized power management scheme that allows the main high power radio to participate in contact discovery, but searches for contacts less frequently than the low power radio. Each radio controls its frequency by a time interval, called *wake-up interval*, to wake up and search for contacts. This wake-up interval can be used as a tuning parameter to trade between energy savings and the performance of message delivery. In addition, for the case in which traffic load can be predicted, we devise approximation algorithms to determine the optimal wake-up intervals that discover enough contacts to handle a given traffic load, while minimizing the overall energy consumption.

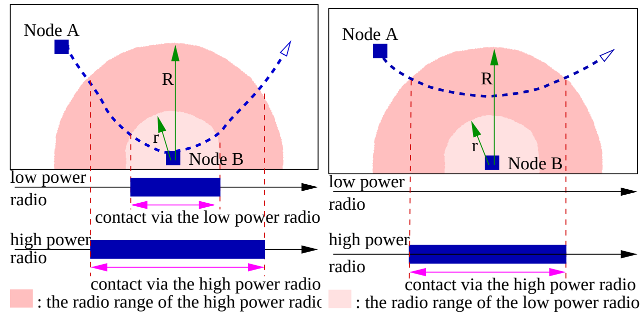
We evaluate our mechanisms using ns-2 simulations with two node movement scenarios. Our results show that the generalized power management mechanism could augment the usefulness of the low power radio and achieve better energy efficiency than mechanisms relying only on one radio for contact discovery. Also, our approximation algorithms help to save 73% to 93% of energy compared to the case without power management. However, our simulation results show that while an additional low power radio does reduce the energy consumption needed for discovery, the improvement could be negligible in mobile DTNs. While this seems to contradict the results of previous studies [25, 28, 21], the differences lie in the density and mobility in the network. In particular, previous research has targeted nomadic computing scenarios where the density of nodes is much higher. In these situations the low-power radio can discover contact opportunities as well as the high-power radio. In DTNs, the low-power radio may discover much fewer contacts than the high-power radio, thus lowering the overall efficiency. Also, if additional information about contacts and traffic load is available, a node even with one radio could save considerable energy. As a result, the overall benefits of the hierarchal radio architecture becomes to a level similar to using one radio alone.

The remainder of this paper is organized as follows. In Section 2, we presents our power management framework. Section 3 shows our simulation results to evaluate the performance of our power management under various parameters. In Section 4, we propose wake-up interval estimation for our power management according to the expected traffic load. Section 5 illustrates our simulation results to evaluate the traffic-aware wake-up interval estimation. We discuss related work in Section 6 and conclude this paper in Section 7.

2. DTN RADIO DISCOVERY

In a mobile DTN, two nodes communicate with one another during *contacts* [14] that occur when the two nodes, either mobile or stationary, are within the radio range of one another. If the devices are equipped with multiple radios, the nodes may or may not discover a particular contact opportunity depending on the range of the radios, which radios are active, and the movement trajectory of the two nodes. Figure 1 shows two possible contact scenarios. In Figure 1(a), node A moves along the trajectory shown and node B stays in one location. Node A first enters within the B's high-power radio range and then within the range of the low-power radio of node B. As a result, the nodes have a long contact via their high-power radios and a short contact via their low-power radios. In contrast, Figure 1(b) shows that when node A passes node B using a different trajectory, it only enters the range of the high-power radio of node B. As a result, the nodes have only one contact via their high-power radios.

While the short range radio may discover less contact opportu-



(a) Contacts via both radios

(b) A contact only via the high-power radio

Figure 1: Contacts discovered by the high-power and low-power radios, where R and r are the radio radii of the high-power and low-power radios, respectively

Table 1: Power usage of a Lucent IEEE 802.11 WaveLAN PC Card and a Chipcon CC1000 (unit:W)

Activity	Transmit	Receive	Idle	Sleep
WaveLan PC card	1.3272	0.9670	0.8437	0.0664
Chipcon CC1000	0.0781	0.0222	0.0222	0.00003

nities than the long range radio, it does so at substantially reduced energy costs. Table 1 shows the energy consumption of two sample radios, one high-power radio: 802.11, and one low-power radio: the CC1000 radio found in Mica2 Motes [11, 8, 21]. The energy consumption of each wireless interface depends on whether it is *transmitting*, *receiving*, *idling* (when listening to the wireless medium without transmitting nor receiving), or *sleeping* (when the wireless interface is disabled). When sleeping, a node consumes an order of magnitude less energy than when idling, while an idling node consumes energy at the same order of magnitude as a receiving or transmitting node. In addition, the CC1000 radio consumes an order of magnitude less energy than the 802.11 radio for each activity. Thus, it can discover contacts using substantially less power. However, its outdoor range is limited to 50-100m, while the 802.11 radio has a range of 250-500m.

In this paper, we consider a DTN consisting of mobile nodes as well as stationary nodes, which have two radio interfaces: one with a long radio range and high-power, e.g., a 802.11 wireless card, and the other with a short radio range and low-power, e.g., a CC1000 radio. We only account for the communication energy consumption of a wireless interface and do not consider other sources such as computation or mobility. Also, we assume that nodes have no a-priori knowledge about other nodes' mobility and contacts must be discovered by one or both radios of the nodes. To discover contacts, a radio broadcasts messages called *beacons* periodically. To save energy while discovering contacts, a radio has three power management modes: *search*, *contact*, and *dormant modes*. In the search mode, the radio wakes up periodically to discover a contact. This period is called a *wake-up interval*. In the contact mode, the radio stays awake to exchange messages with other nodes that it previously discovered in the search mode. In the dormant mode, the radio is not used and remains asleep.

Given that the high-power radio is always used, there are four possible variations of this general framework. Table 2 summarizes the power management mechanisms used in this paper. The *Continuous Aware Mechanism (CAM)* uses only the high-power radio of a node. In CAM, the high power radio always stays awake to search for other nodes. The *Power Saving Mechanism (PSM)* also uses only the high-power radio, however it alternates between asleep and awake while discovering contacts. While similar, note that this PSM is not the same as 802.11's PSM mode. The *Short-range-radio-dependent Power Saving Mechanism (SPSM)* uses both low-power and high-power radios of a node. In this mechanism, the low-power radio alternates between sleeping and waking up to discover contacts, while the high-power radio sleeps and is awakened by the low-power radio only after discovering a contact. Finally, the *Generalized Power Saving Mechanism (GPSM)* uses both the low power and high-power radios of a node. In this mechanism, both radios alternate between sleeping and waking up to discover contacts. If a contact is discovered by the low-power radio, the high-power radio is awakened. If a contact is discovered by the high-power radio, the radio stays awake as long as it has contact with the other node. Here we describe each of these mechanisms in detail, with the exception of CAM, which is trivial.

2.1 Power Saving Mechanism (PSM)

In PSM, a node uses only one long-range radio and its radio periodically sleeps and wakes up to save energy while discovering contacts. Such a scheme was first described in our previous work [18] and we summarize it below for completeness.

We describe the wake-up behavior using three quantities: *beacon window*, *beacon period*, and *wake-up interval*. The beacon window is a time period when the radio wakes up and chooses a random time to transmit a beacon. A beacon period is the time between the beginning of two consecutive beacon windows in the contact mode. Finally, a wake-up interval is the time between two consecutive wake-up's in the search mode, which can be enlarged as a multiple of a beacon period. Note that we assume that nodes have synchronized clocks from a source such as GPS, and thus the beacon windows can be synchronized to start on common, discrete intervals.

These time periods are used as illustrated in Figure 2 when a node contacts only one node. Initially, the radio of a node is in the search mode since it is not in contact with node k. In the beginning of a beacon window, it chooses a random time within the beacon window to broadcast a beacon. If it does not receive another node's beacon, the radio sleeps at the end of the beacon window and wakes up at the beginning of the next beacon window. If the radio receives a beacon, it enters the contact mode, in which it stays awake to exchange messages. In the contact mode it continues to send a beacon at every beacon period and listens for beacons from the same node. If the radio fails to receive a certain number of beacons consecutively, it considers the contact is terminated and returns to the search mode. When a node contacts multiple nodes, its radio should consider multiple contact states to transit between the power management modes. The detailed procedure and algorithm can be found in [18].

2.2 Short-range-radio-dependent Power Saving Mechanism (SPSM)

In SPSM, a node depends only on the low-power radio to discover contacts. As in PSM, nodes have synchronized clocks and both radios have their own three time periods to synchronize contact discovery procedure among nodes.

This scheme is identical to PSM except that the low-power radio conducts PSM's search mode as illustrated in Figure 3. If the low-power radio detects a contact, it wakes up the high-power radio, which then enters the contact mode. In the contact mode, the high-power radio stays awake to exchange messages, using the beacons to detect when the contact ends. At the same time, the low-power radio continues to search for other contacts. When all the contacts are terminated, the high-power radio sleeps in the dormant mode and the low-power radio continues to search.

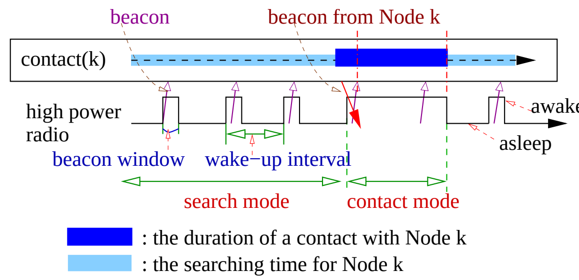


Figure 2: Transition between power management modes when a node has contacts with only one node, node k, using PSM

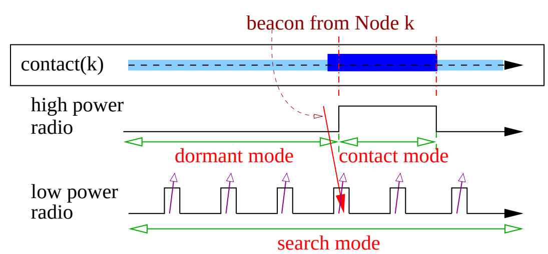


Figure 3: Transition between power management modes when a node has contacts with only one node, node k, using SPSM

2.3 Generalized Power Saving Mechanism (GPSM)

In GPSM, a node utilizes both radios to discover contacts. The two radios have separate wake-up intervals, beacon periods, and beacon windows. For instance, the high-power radio may have a larger wake-up interval than the low power radio, in which case the low-power radio searches for contacts more frequently than the high-power radio.

Figure 4 illustrates the power management with an example scenario. Initially, a node has no contact, so that both of its radios alternate between sleeping and waking up to send and listen for beacons in the search mode. If the low-power radio receives a beacon from node k, it wakes up the high-power radio and keeps searching for other contacts. If the high-power radio receives a beacon from node k, it enters the contact mode and stays awake to exchange messages. It also sends and listens for beacons from the same node. If the high-power radio does not receive a certain number of beacons consecutively from the same node, it considers that the contact is terminated and enters the search mode.

This mechanism is a generalized scheme that includes PSM and SPSM at its two extremes. If we set the wake-up interval of the low-power radio to infinity, GPSM works like PSM. Also, if we set the wake-up interval of the high-power radio to infinity, it works like SPSM.

3. PERFORMANCE COMPARISON

To provide some insight into the performance comparison of these schemes, we provide a set of simulation results. Specifically,

Table 2: Power management mechanisms depending on how the radios are used

Power management	low-power radio	high-power radio
CAM	Not used	Always on
PSM	Not used	sleep/wake-up cycling to discover contacts
SPSM	Sleep/wake-up cycling to discover contacts	Awakened by the low-power radio
GPSM	Sleep/wake-up cycling to discover contacts	Sleep/wake-up cycling to discover contacts, *and* Awakened by the low-power radio

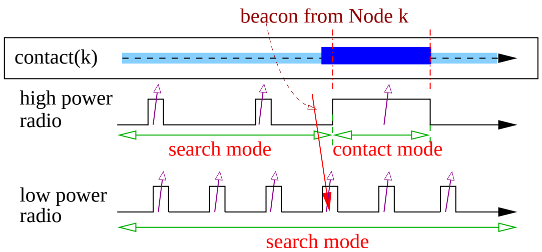


Figure 4: Transition between power management modes when a node has contacts with only one node, node k, using GPSM

we investigate the impact of the two most important parameters to the contact discovery performance: the range of the low-power radio and the wake-up interval of the high-power radio. We consider two metrics: (1) *contact discovery ratio*, which is the discovered contact time divided by the total contact time that the high-power radio could have discovered when using CAM, and (2) *energy efficiency*, which is the average amount of discovered contact time per unit energy used. In other words, we measure how much energy the system spends to find a certain amount of message transfer time—the more transfer time discovered per joule of energy, the higher efficiency is.

We use the ns-2 simulator with the following parameters. We use 802.11 MAC layer for both interfaces at different channels. Also, both interfaces set the beacon period to 2 seconds and the beacon window to 300ms. Each simulation runs for 50 hours of simulated time and each point of our graphs represents the average of ten runs. For the experiment we use the energy consumption of an 802.11 and a CC1000 radio as shown in Table 1. For the low-power radio, the radio range and the data rate are 100m and 76.8Kb/s, respectively, with one exception. In the first experiment, we wanted to show the impact of different radio ranges on the discovery process, so we used a hypothetical radio based on the CC1000's energy consumption. For ranges shorter and longer then the 100m range of the CC100 radio, we modeled the transmission power based on the Two-Ray ground reflection model [23]. In all cases the high-power radio has a fixed radio radio range and data rate of 250m and 2Mb/s, respectively.

To simulate node movement, we consider two node movement scenarios: Random-Waypoint (RWP) [15] and Message Ferrying [34]. These scenarios have the following characteristics. In the RWP scenario, nodes may pass by each other at long distances. In the MF scenario, a mobile node visits other nodes and approaches them at shorter distance. We simulate them as follows. In RWP, a network consists of 20 nodes, which move in the Random-Waypoint model, in 10km$\times$10km area. In MF, a network consists of nine stationary nodes in a grid of 5km$\times$5km area sparsely. Then, the ferry visits each node in order and repeats the route. As a result, stationary nodes are too far away to communicate with each other and only the ferry provides network connectivity by visiting each node from time to time. In both models, a mobile node selects a random speed between 5m/s and 10m/s and moves toward its destination.[1] When it reaches a destination, it pauses there for a *pause time* that is exponentially distributed with an average of 30 seconds. When the pause time is up, the node moves toward the next destination.

3.1 Impact of radio ranges

In Figure 5, we investigate the impact of the short range of the low power radio to show the resulting performance of SPSM as the range varies from 3m to 150m. In this set of simulations, the wake-up interval of the high-power radio is set to 8 seconds and that of the low-power radio is set to 2 seconds.

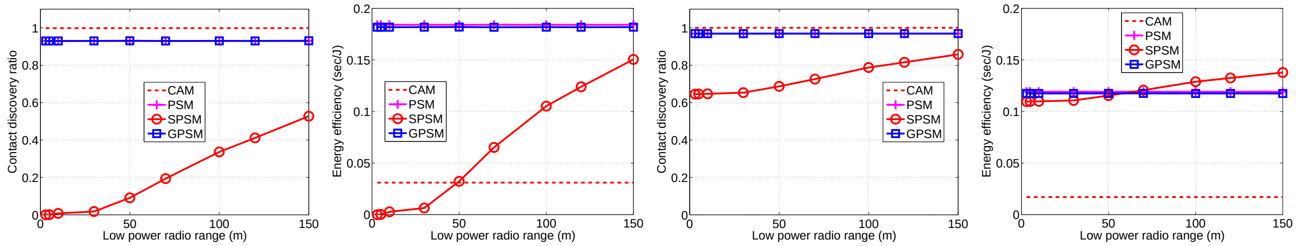
Figure 5(a) shows that the contact discovery ratios of GPSM and PSM are over 90%, while that of SPSM is much lower than that of others. This demonstrates that SPSM suffers from a serious limitation in such a mobility scenario: nodes using just a short-range radio to discover contacts miss a lot of contacts because they may often pass by each other at long distances. Figure 5(a) also shows that the contact discovery ratio of SPSM improves as its radio range gets longer, even though we have accounted for the increased energy consumption needed to support that range. Also, Figure 5(b) shows that the energy efficiency of SPSM is much lower than that of others because SPSM keeps consuming energy to search without discovering many contacts, especially when the low-power radio range is short. Therefore, nodes may use GPSM to utilize the two radio architecture rather than SPSM in this mobility scenario. However, the results of this experiment are highly dependent on the type of mobility found in the network. In a more structured environment where nodes pass much closer to one another as in the MF scenario, SPSM performs better than in this scenario.

In the MF scenario, Figure 5(c) shows that the contact discovery ratios of all mechanisms are over 60% even when the range of the low power radio is 3m/s. In MF, a ferry visits each node closely, so that nodes even with a short radio range could still discover most of their contacts. The contact discovery ratio of SPSM is lower than that of others only because nodes using SPSM discover contacts later than nodes using other mechanisms due to the short range. In addition, Figure 5(d) shows that the energy efficiency of SPSM outgrows those of PSM and GPSM when the low power radio range is longer than 60m. Therefore, the efficiency of using SPSM depends not only on the range of the low power radio, but also on the mobility characteristics of nodes.

3.2 Impact of Wake-up Intervals

In Figure 6, we show the impact of the wake-up interval of the high-power radio to the performance of contact discovery as the interval varies from 2 to 1024 seconds to show how it trades between energy and contact discovery performance. The wake-up interval of the low-power radio is set to 2 seconds for both SPSM and GPSM.

[1]We use a non-zero minimum sped to adjust the stability problem of RWP as described in [33].

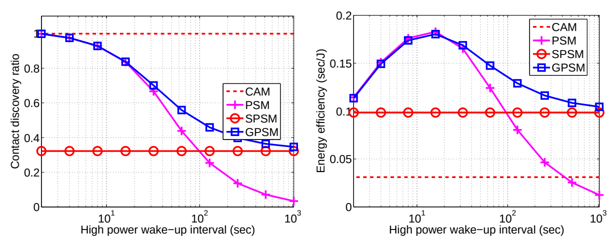


(a) contact discovery ratio (RWP) (b) energy efficiency (RWP) (c) contact discovery ratio (MF) (d) energy efficiency (MF)

Figure 5: The impact of the low power radio range in the RWP and MF scenarios

Figure 6(a) shows that the contact discovery ratio of PSM decreases from 100% to below 10% as the wake-up interval increases. On the other hand, GPSM discovers more than 37% of contacts for all wake-up intervals because the low-power radio assists the discovery. In addition, its discovery ratio is always more than that of SPSM because of the high-power radio.

Figure 6(b) shows that the energy efficiency of GPSM and PSM increases and then decreases as the wake-up interval decreases. Once most of the contacts are discovered, using smaller wake-up intervals wastes energy without discovering much more contacts. Also, Figure 6(b) shows that the energy efficiency of GPSM outperforms those of PSM and SPSM for all wake-up intervals.



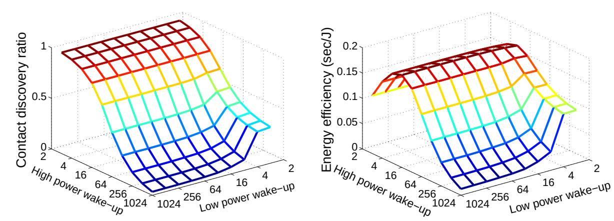
(a) contact discovery ratio (b) energy efficiency

Figure 6: The impact of wake-up intervals of the high-power radio in the RWP scenario

Figures 7(a) and 7(b) show the contact discovery ratio and energy efficiency of GPSM as both wake-up intervals of the high-power and low-power radios vary from 2 to 1024 seconds. The maximum contact discovery ratio is achieved when both wake-up intervals are 2 seconds, while the the optimal energy efficiency is achieved when both wake-up intervals are 16 seconds.

This experiment demonstrates that not only the wake-up interval of the radio greatly impacts energy efficiency, but also the usefulness of the second radio is highly dependent on that interval. Additionally, this does not answer the question as to how to set the interval in the first place. In the next section, we provide this as an analytical result when additional information about contacts and traffic load is available.

4. TRAFFIC-AWARE WAKE-UP INTERVAL ESTIMATION



(a) contact discovery ratio (b) energy efficiency

Figure 7: The impact of wake-up intervals for GPSM in the RWP scenario (unit: seconds)

The critical issue in all of the power management mechanisms is determining the proper wake-up interval. In each mechanism, the wake-up intervals can be used to trade between energy and delivery performance. Specifically, when the wake-up intervals are long, energy can be saved at the cost of missing contacts, which in turn results in poor delivery performance. When the wake-up intervals are short, more energy will be expended while discovering more contacts and improving delivery performance. The key lies in discovering just enough contacts to deliver a node's messages. We state the problem as follows: *For each node, find the wake-up intervals that leads to discover enough contacts to deliver the expected traffic load while minimizing energy consumption.* While such an optimization targets bandwidth, other optimization criteria are possible and can be fit into this framework.

To formulate the problem, we assume that statistical information about contacts and traffic load between each pair of nodes is available. This information is often already available in a DTN: nodes observe and exchange the history of contacts and traffic load to make efficient routing decisions [6, 14].

To address the problem, we define the *contact arrival rate* as the number of contacts between two nodes over a unit time and *expected bandwidth* as the maximum amount of messages that can be delivered by the discovered contacts between two nodes over a unit time. With these definitions, we can estimate the expected bandwidth for given wake-up intervals using contact duration and contact arrival rate per pair of nodes. Unfortunately, the distribution of inter-arrival times and contact durations is generally not known, especially for many common mobility models [4]. Without this, it is not possible to develop general, optimal algorithms. Therefore,

Table 3: Notation used in the wake-up interval estimation, where the subscript ij indicates that the parameter is specific to the link between node i and node j

N	the set of nodes in a network
R	the radio range of the high-power interface
r	the radio range of the low-power interface
θ	the bandwidth of the high-power interface
f_{ij}	the traffic load on the link (i, j)
w^h, w^l	the wake-up intervals of the high-power and low-power radios, respectively
$\lambda^h_{ij}, \lambda^l_{ij}$	the contact arrival rates when R is used and when r is used, respectively
d^h_{ij}, d^l_{ij}	the contact duration when R is used and when r is used, respectively
$c^{psm}_{ij}(w^h)$	the expected amount of a contact that can be discovered by PSM for a given w^h
$c^{spsm}_{ij}(w^l)$	the expected amount of a contact that can be discovered by SPSM for a given w^l
$c^{gpsm}_{ij}(w^h, w^l)$	the expected amount of a contact that can be discovered by GPSM for given (w^h, w^l)

we devise an approximation by *measuring* contact durations from a mobility model and assume that contacts arrive according to a Poisson process. In Section 5, we validate this approximation and show that it works well in practice. We plan to extend this to on-line algorithms that measure and react to changing contact opportunities and traffic load. Note that the notation used in the wake-up interval estimation is summarized in Table 3.

4.1 Wake-Up Interval Estimation for PSM

Recall that PSM uses only the high-power radio to discover contacts. Since individual nodes have different traffic loads, we choose a different optimal wake-up interval for each node. However, given that nodes wake up at different rates, we must ensure that the nodes can still synchronize their wake-ups so that one node hears another node's beacon. To do this, we choose the wake-up intervals from a set that are a multiple of the interval between another node's beacons, which we refer to as the beacon period. Thus, we assume that a network operator provides a set of wake-up interval candidates as follows:

$$W^h = \{w^h \mid w^h = 2^k b^h,\ k = 0, 1, 2, ..K\}, \tag{1}$$

where b^h is a beacon period of the high-power radio and K is a non-negative integer.

From W^h, we determine the optimal wake-up interval of the high-power radio for node i as follows. First, we estimate the expected bandwidth on the link (i, j) for each wake-up interval $w^h \in W^h$, as illustrated in Figure 8. Initially, an opportunity to have a contact on the link (i, j) starts at time t after the termination of the last wake-up. We ignore a beacon window because it is very short. Because we assume that contacts arrive as a Poisson process, the arrival time of a contact is approximately uniformly distributed within a wake-up interval, i.e., $t \sim$ uniform(0, w^h). At the next wake-up, the contact can be discovered if the contact is longer than the remaining time until the next wake-up, i.e., $w^h - t < d^h_{ij}$, where d^h_{ij} is the contact duration on the link (i, j) that can be discovered by the high-power radio. In addition, its length is the contact duration less the remaining time until the next wake-up, i.e., $d^h_{ij} - (w^h - t)$. Thus, the expected discovered contact time $c^{psm}_{ij}(w^h)$ of a contact for a given w^h is calculated as follows. If $w^h \le d^h_{ij}$,

$$c^{psm}_{ij}(w^h) = \int_0^{w^h} \frac{1}{w^h}(d^h_{ij} - w^h + t)\,\mathrm{d}t. \tag{2}$$

Otherwise (i.e., if $w^h > d^h_{ij}$),

$$\begin{aligned} c^{psm}_{ij}(w^h) &= \int_0^{w^h - d^h_{ij}} \frac{1}{w^h} \cdot 0\,\mathrm{d}t \\ &+ \int_{w^h - d^h_{ij}}^{w^h} \frac{1}{w^h}(d^h_{ij} - w^h + t)\,\mathrm{d}t. \end{aligned} \tag{3}$$

The first integral corresponds to the case when the contact is shorter that the wake-up interval, and the contact opportunity does not overlap with any of the beacon windows. The second case corresponds to the case when the contact duration can be discovered by a wake-up, but the node misses the first part of the contact. As a result,

$$c^{psm}_{ij}(w^h) = \begin{cases} d^h_{ij} - \frac{1}{2}w^h & \text{if } w^h \le d^h_{ij} \\ \frac{(d^h_{ij})^2}{2w^h} & \text{otherwise} \end{cases} \tag{4}$$

Then, the expected bandwidth on the link (i, j) is $\lambda^h_{ij} \cdot \theta \cdot c^{psm}_{ij}(w^h)$ for a given w^h, where λ^h_{ij} is the contact arrival rate when the high-power radio is used on the link (i, j), and θ is the bandwidth of the high-power radio.

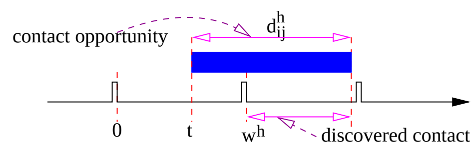


Figure 8: A discovered contact time by PSM for a given w^h

Secondly, we find the set of wake-up intervals, w^h, that provide bandwidth greater than or equal to the traffic load on the link (i, j). We choose the wake-up interval from this set, by finding the interval that consumes the least amount of energy. In the case of PSM, this is straightforward as it is the maximum wake-up interval w^h_{ij} in the set, i.e.,

$$w^h_{ij} = \max\left\{w^h \mid \lambda^h_{ij} \cdot \theta \cdot c^{psm}_{ij}(w^h) \ge f_{ij},\ w^h \in W^h\right\}, \tag{5}$$

where f_{ij} is the traffic load on the link (i, j). Then, the resulting w^h_{ij} is the wake-up interval that will consume the least amount of energy while satisfying the bandwidth constraint on the link (i, j).

Since the node contacts multiple other nodes, and it does not know which node it will discover next, it must choose the minimum wake-up interval among all of the wake-up intervals it computed for each outgoing link, w^h_{ij}, i.e.,

$$w^h_i = \min\{w^h_{ij} \mid j \in N - \{i\}\}, \tag{6}$$

where N is the set of nodes in the network. Then, the resulting w^h_i is the wake-up interval that consumes the least amount of energy while satisfying the bandwidth constraints for all the links of node i. This result is optimal for the set of discrete wake-up intervals the algorithm considers.

4.2 Wake-Up Interval Estimation for SPSM

In contrast with PSM, SPSM relies solely on the low-power radio to discover contacts. As shown in Figure 1, the length of a contact via the low-power radio is shorter than that via the high-power radio. Thus, once a contact is discovered via the low-power radio, the high-power radio monitors the state of the contact and extends the contact time beyond the time the node leaves the range of the low-power radio. This extended amount of a contact is denoted as δ_{ij} for the link (i, j). This δ_{ij} can be observed by having a node maintain its contact states by both radios and estimate the time difference between the termination of their contacts, i.e., (the termination of a contact discovered by the high-power radio - that of the corresponding contact by the low-power radio). This extension makes the estimation of the expected bandwidth of SPSM different from that of PSM. Except for that, the wake-up interval estimation procedure of SPSM is identical to that of PSM.

Figure 9 illustrates an example scenario to estimate the expected bandwidth on the link (i, j). Initially, a contact starts at time t after the termination of the last wake-up. At the next wake-up, the contact can be discovered if the contact by the low power radio is longer than the remaining time until the next wake-up, i.e, $w^l - t < d^l_{ij}$, where d^l_{ij} is the contact duration on the link (i, j) when the low power radio is used. In addition, the contact will be extended by δ_{ij} by the long range of the high power radio. As a result, the discovered amount of a contact is the summation of the contact duration by the low power radio and the extended contact time by the high power radio less the remaining time until the next wake-up, i.e., $d^l_{ij} + \delta - (w^l - t)$. Thus, the expected discovered contact time of a contact is calculated as follows: If $w^l \leq d^l_{ij}$,

$$c^{spsm}_{ij}(w^l) = \int_0^{w^l} \frac{1}{w^l}(d^l_{ij} + \delta_{ij} - w^l + t)\,\mathrm{d}t. \tag{7}$$

Otherwise (i.e., if $w^l > d^l_{ij}$),

$$\begin{aligned} c^{spsm}_{ij}(w^l) &= \int_0^{w^l - d^l_{ij}} \frac{1}{w^l} 0 \cdot\,\mathrm{d}t \\ &+ \int_{w^l - d^l_{ij}}^{w^l} \frac{1}{w^l}(d^l_{ij} + \delta_{ij} - w^l + t)\,\mathrm{d}t \end{aligned} \tag{8}$$

As a result,

$$c^{spsm}_{ij}(w^l) = \begin{cases} d^l_{ij} + \delta_{ij} - \frac{1}{2}w^l & \text{if } w^l \leq d^l_{ij} \\ \frac{d^l_{ij}(d^l_{ij} + 2\delta_{ij})}{2w^l} & \text{otherwise} \end{cases} \tag{9}$$

Then, the expected bandwidth between nodes i and j is $\lambda^l_{ij} \cdot \theta \cdot d^{psm}_{ij}(w^l)$ for a given w^l, where λ^l_{ij} is the contact arrival rate on the link (i, j) when the low power radio is used. The rest of the procedure to determine the optimal wake-up interval is omitted because it is identical to that of PSM.

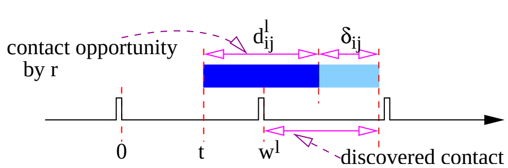


Figure 9: A discovered contact time by SPSM for a given w^l

4.3 Wake-Up Interval Estimation for GPSM

This power management uses both high-power and low-power radios to discover contacts. Since contacts can be discovered by either of the radios, the wake-up interval estimation procedure is more complicated than that of the other mechanisms. In brief, we determine the wake-up intervals for node i as follows. First, we estimate the expected bandwidth on the link (i, j) for each pair of wake-up intervals (w^h, w^l) in a given set of discrete wake-up interval pairs. Secondly, we find a set S_{ij} of wake-up interval pairs that provide enough bandwidth to consume the expected traffic load on the link (i, j) for each $j \in N - \{i\}$. Third, we find the pair of wake-up intervals (w^h_{ij}, w^l_{ij}) in S_{ij} that will consume the least amount of energy assuming that node i contacts only node j, so both nodes choose the same pair of wake-up intervals that satisfies the bandwidth requirement on their link and possibly consumes the least amount of energy. Finally, the node chooses the minimum wake-up intervals w^h_i and w^l_i among w^h_{ij} and w^l_{ij}, respectively. Then, the resulting (w^h_i, w^l_i) is the pair of wake-up intervals that consumes the least amount of energy while satisfying the bandwidth constraints for all the links of node i.

The detailed procedure is as follows. To estimate the expected bandwidth per link, we first calculate the expected discovered contact time of a contact, in which a pair of nodes can communicate with each other through their high power radios. Among the contacts that can be discovered by the high power radios, some of them can also be discovered by the low power radio and the others cannot, as shown in Figure 1. To distinguish these two classes in an equation, we denote α_{ij} as the ratio of contacts that can be discovered by the low power radio to those that can be discovered by the high power radio. Then, the expected discovered contact time $c^{gpsm}_{ij}(w^h, w^l)$ can be stated as follows:

$$c^{gpsm}_{ij}(w^h, w^l) = \alpha_{ij}\bar{c}^{gpsm}_{ij}(w^h, w^l) + (1 - \alpha)c^{psm}_{ij}(w^h), \tag{10}$$

where $\bar{c}^{gpsm}_{ij}(w^h, w^l)$ is the expected contact time that can be discovered by both radios on the link (i, j) for given (w^h, w^l), and $c^{psm}_{ij}(w^h)$ is defined as before.

The contacts that can be discovered by both radios can also be categorized into subclasses because each radio has a different probability to discover a contact depending on its choice of a wake-up interval. Thus, we categorize them into three classes: (1) contacts that will be discovered by both radios, (2) contacts that can be discovered by the high power radio, but not by the low power radio, and (3) contacts that can be discovered by the low power radio, but not by the high power radio. To represent these classes in an equation, we denote p^p_{ij} as the probability to discover a contact by the high power radio and p^s_{ij} as the probability to discover a contact by the low power radio on the link (i, j). Since the contact durations are constant and contacts are distributed uniform randomly,[2]

$$p^p_{ij} = \begin{cases} \frac{d^h_{ij}}{w^h} & \text{if } d^h_{ij} \leq w^h \\ 1 & \text{otherwise.} \end{cases} \tag{11}$$

$$\tag{12}$$

Similarly,

$$p^s_{ij} = \begin{cases} \frac{d^l_{ij}}{w^l} & \text{if } d^l_{ij} \leq w^l \\ 1 & \text{otherwise.} \end{cases} \tag{13}$$

$$\tag{14}$$

Thus, $\bar{c}^{gpsm}_{ij}(w^h, w^l)$ is the summation of these three classes: i.e.,

$$\begin{aligned} \bar{c}^{gpsm}_{ij}(w^h, w^l) &= \hat{c}^{gpsm}_{ij}(w^h, w^l) \cdot p^p_{ij} \cdot p^s_{ij} \\ &+ c^{psm}_{ij}(w^h) \cdot (1 - p^s_{ij}) \\ &+ c^{spsm}_{ij}(w^l) \cdot (1 - p^p_{ij}), \end{aligned} \tag{15}$$

where $\hat{c}^{gpsm}_{ij}(w^h, w^l)$ is the expected amount of a contact that will

[2]It is because we assume that contacts arrive as a Poisson process.

be discovered by both radios for given (w^h, w^l), and $c_{ij}^{psm}(w^h)$ and $c_{ij}^{spsm}(w^l)$ are defined as before.

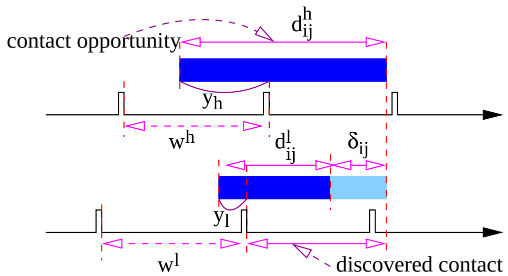


Figure 10: A discovered contact time by both radios using GPSM for a given (w^h, w^l)

The expected amount of a contact that will be discovered by both radios, $\widehat{c}_{ij}^{gpsm}(w^h, w^l)$, is illustrated in Figure 10. Initially, a contact opportunity starts y_h time before the wake-up of the high power radio and y_l time before the wake-up of the low power radio. Since we assume that this contact will be discovered by both radios, y_h should be between 0 and $\min(w^h, d_{ij}^h)$. Thus, $y_h \sim$ uniform$(0, \min(w^h, d_{ij}^h))$. Similarly, $y_l \sim$ uniform$(0, \min(w^l, d_{ij}^l))$. In addition, if the discovered contact by the high power radio is longer than that by the low power radio, i.e., $d_{ij}^h - y_h > (d_{ij}^l + \delta_{ij}) - y_l$, the discovered amount of the contact is $d_{ij}^h - y_h$. Otherwise, the discovered amount of the contact is $d_{ij}^l + \delta_{ij} - y_l$. Thus, the expected contact time of a contact that will be discovered by both radios is calculated as follows: If $w^h \leq d_{ij}^h$ and $w^l \leq d_{ij}^l$,

$$\begin{aligned}\widehat{c}_{ij}^{gpsm}(w^h, w^l) &= \int_0^{w^l} \int_0^{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l} \frac{(d_{ij}^h - y_h)}{w^h w^l} \mathrm{d}y_h \mathrm{d}y_l \\ &+ \int_0^{w^l} \int_{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l}^{w^h} \frac{(d_{ij}^l + \delta_{ij} - y_l)}{w^h w^l} \mathrm{d}y_h \mathrm{d}y_l. \end{aligned} \tag{16}$$

If $w^h \leq d_{ij}^h$ and $w^l > d_{ij}^l$,

$$\begin{aligned}\widehat{c}_{ij}^{gpsm}(w^h, w^l) &= \int_0^{d_{ij}^l} \int_0^{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l} \frac{(d_{ij}^h - y_h)}{w^h d_{ij}^l} \mathrm{d}y_h \mathrm{d}y_l \\ &+ \int_0^{d_{ij}^l} \int_{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l}^{w^h} \frac{(d_{ij}^l + \delta_{ij} - y_l)}{w^h d_{ij}^l} \mathrm{d}y_h \mathrm{d}y_l. \end{aligned} \tag{17}$$

If $w^h > d_{ij}^h$ and $w^l \leq d_{ij}^l$,

$$\begin{aligned}\widehat{c}_{ij}^{gpsm}(w^h, w^l) &= \int_0^{w^l} \int_0^{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l} \frac{(d_{ij}^h - y_h)}{d_{ij}^h w^l} \mathrm{d}y_h \mathrm{d}y_l \\ &+ \int_0^{w^l} \int_{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l}^{d_{ij}^h} \frac{(d_{ij}^l + \delta_{ij} - y_l)}{d_{ij}^h w^l} \mathrm{d}y_h \mathrm{d}y_l. \end{aligned} \tag{18}$$

Otherwise (i.e., if $w^h > d_{ij}^h$ and $w^l > d_{ij}^l$),

$$\begin{aligned}\widehat{c}_{ij}^{gpsm}(w^h, w^l) &= \int_0^{d_{ij}^l} \int_0^{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l} \frac{(d_{ij}^h - y_h)}{d_{ij}^h d_{ij}^l} \mathrm{d}y_h \mathrm{d}y_l \\ &+ \int_0^{d_{ij}^l} \int_{d_{ij}^h - d_{ij}^l - \delta_{ij} + y_l}^{d_{ij}^h} \frac{(d_{ij}^l + \delta_{ij} - y_l)}{d_{ij}^h d_{ij}^l} \mathrm{d}y_h \mathrm{d}y_l. \end{aligned} \tag{19}$$

Along with Equations 10-19, we find the set S_{ij} of wake-up interval pairs that provide more than or equal to the required bandwidth on the link (i, j) as follows:

$$S_{ij} = \{(w^h, w^l) \mid \lambda_{ij}^h \cdot \theta \cdot c_{ij}^{gpsm}(w^h, w^l) \geq f_{ij}\}, \tag{20}$$

where f_{ij} and λ_{ij} are the traffic load and the contact arrival rate on the link (i, j), respectively.

Third, we find the pair of wake-up intervals (w_{ij}^h, w_{ij}^l) in S_{ij} that will consume the least amount of energy assuming that node i contacts only node j, so both nodes choose the same pair of wake-up intervals that satisfies the bandwidth constraint on their link and possibly consumes the least amount of energy. In previous mechanisms, the maximum wake-up interval achieves the maximum energy savings among candidates. However, in GPSM, it is not obvious whether increasing one wake-up interval will result in energy savings if the other wake-up interval has to be decreased. Thus, we estimate the expected energy consumption for each pair of wake-up intervals in S_{ij} to find the pair that minimizes the energy consumption. To represent the energy consumption of GPSM, the transmission, reception, idle, and sleeping power of the high power radio are denoted as P_h^t, P_h^r, P_h^i, and P_h^s, respectively. Similarly, those of the low power radio are denoted as P_l^t, P_l^r, P_l^i, and P_l^s, respectively. Also, the ratio of a beacon window to the unit time of the high power is denoted as a_h, and that of the low power radio is denoted as a_l. Then, the energy consumption of GPSM is the summation of energy consumption by the low power radio in general, that of the high power radio in the searching mode, and that of the high power radio in the contact mode. We ignore the transmission energy of beacons because the size of a beacon is so small that its additional energy consumption for transmitting beyond idling is negligible. As a result, the energy consumption $E(w^h, w^l)$ of GPSM for given (w^h, w^l) in a unit time is estimated as follows:

$$\begin{aligned} E(w^h, w^l) &= P_l^s + P_h^s + \tfrac{1}{w^l}\left\{(P_l^i - P_l^s)a_l\right\} \\ &+ \tfrac{1 - \lambda_{ij}^h c_{ij}^{gpsm}(w^h, w^l)}{w^h}\left\{(P_h^i - P_h^s)a_h\right\} \\ &+ (P_h^i - P_h^s)\lambda_{ij}^h c_{ij}^{gpsm}(w^h, w^l), \end{aligned} \tag{21}$$

where node i contacts only node j. With this estimation of energy consumption, we select the pair of wake-up intervals (w_{ij}^h, w_{ij}^l) that minimizes $E(w^h, w^l)$, where $(w^h, w^l) \in S_{ij}$.

Finally, the node chooses the minimum wake-up intervals w_i^h and w_i^l among w_{ij}^h and w_{ij}^l, respectively, i.e.,

$$w_i^h = \min\{w_{ij}^h \mid j \in N - \{i\}\} \tag{22}$$

and

$$w_i^l = \min\{w_{ij}^l \mid j \in N - \{i\}\}, \tag{23}$$

where N is the set of nodes in the network. Then, the resulting (w_i^h, w_i^l) is the pair of wake-up intervals that consumes the least amount of energy approximately while satisfying the bandwidth constraints for all the links of node i.

5. PERFORMANCE EVALUATION

Our goal in evaluating our traffic-aware optimization process is to show two things. First, we show that our analytical model can accurately predict the fraction of contacts for any particular wake up interval. If the predicted number of contacts is correct, then the wake up interval can be tuned to a particular traffic load. Second, we show that these wake-up mechanisms save significant energy in a DTN node; and compare the use of single and multiple radio search mechanisms.

To show this we use the same Random Way Point model from earlier as well as a Message Ferrying (MF) mobility model [34]. In MF the network consists of 12 stationary nodes and eight mobile nodes, called ferries. We place stationary nodes in a grid of 5km×5km area sparsely. Then a ferry visits each node in order and repeats the route, starting at different locations. The key differences between the RWP and MF scenarios is the distance that nodes pass one another: in the RWP contacts occur at much larger distances than in the MF scenario.

5.1 Contact Discovery

Figure 11 shows how close our estimation of contact discovery in Section 4 in comparison to the actual contact discovery. The ratio is the fraction of possible contact opportunities discovered. The possible contacts are those the node could have discovered using the high-power radio in an always on mode (CAM). Each line represents the estimated contact discovery ratio from our model and the simulated contact discovery ratio of each power management in RWP and MF scenarios as indicated. Each scenario has a pair of nodes in a deployment area and each simulation runs for 500 simulation hours. As Figure 11 shows, our estimation could predict the contact discovery ratio close to the simulation results. GPSM tends to have more error than other mechanisms due to its complexity, while its estimation is still close to the simulated results. These graphs are representative for other pairs of wake-up intervals in our evaluation.

5.2 Traffic-Aware Power Management

Given the accuracy in determining the contacts resulting from a particular wake-up interval, we compare the schemes using our traffic-aware wake-up interval estimation. We consider the following metrics: (1) *normalized energy consumption* that is the total energy consumption of each power management case divided by that of CAM, and (2) *delivery ratio* that is the ratio of successfully delivered messages to (the total number of generated messages - the number of remaining messages in the network) by the end of a simulation. In simulations, a message loss occurs when a message buffer overflows at a node in the middle of a routing path because the node attempts to store messages beyond the limitation of its buffers. The routing path selection, traffic generation, and additional simulation results can be found in the technical report [17].

Figure 12 shows the impact of traffic-aware optimization to the power management performance in the RWP and MF scenarios as the traffic load varies from 0.016Kb/s to 54Kb/s. We compare all of the schemes with CAM to observe how much energy can be saved. Also, we compare it with a PSM when the traffic load cannot be predicted. In such a case, we use a fixed wake-up interval. We chose this as the interval that uses the least amount of energy to discover each contact. This allows us to compare a traffic-aware mechanism with one that neglects any knowledge of traffic and focuses solely on energy efficient discovery. In our scenarios, such a wake-up interval for PSM is 16 seconds and the corresponding curve is indicated by "PSM-16" in Figure 12.

In Figures 12(a) and (b), we illustrate the simulation results in the RWP scenario. Figure 12(a) shows that all mechanisms consume energy only from 7% to 27% compared to no power management. Also, it shows that as the traffic load becomes heavier, all mechanisms with traffic-aware optimization consumes more energy because they choose smaller wake-up intervals and end up discovering more contacts. Among these mechanisms, SPSM energy consumption is relatively flat. As the load grows, SPSM searches for contacts as aggressively as it can. However, as a result, Figure 12(b) shows that SPSM has a low delivery ratio when the traffic load is more than 1.6Kb/s. This is because SPSM relies on the low-power radio, which has insufficient range to discover enough contacts to handle its traffic. On the other hand, PSM and GPSM achieve more than 90% delivery ratio for all traffic loads, which is close to the delivery ratio of CAM. In this RWP scenario, GPSM works similarly to PSM because nodes pass by each other at long distances and most of their contacts are discovered by the high power radio. This shows that GPSM can correctly adapt to that mobility scenario. Finally, the energy consumption of PSM-16 is almost constant because of its fixed wake-up interval. The comparison with PSM-16 shows that power management with traffic-aware optimization saves more energy than PSM-16 while delivering the same amount of messages when the traffic load is light. When traffic load is heavy, PSM and GPSM consume more energy, but at the same time deliver more messages than PSM-16. Thus, the additional information about traffic load helps to enhance the performance of power management.

In Figures 12(c) and (d), we illustrate the simulation results in the MF scenario. Figure 12(c) shows that GPSM and SPSM consumes less energy than PSM for most traffic loads. In the MF scenario, ferries visit each node closely, so nodes can discover most of the contacts by the short radio range of the low power radio while saving energy. In this case, our wake-up interval estimation for GPSM selects similar wake-up intervals for the low power radio as SPSM and infinity for the high power radio. As a result, SPSM and GPSM consume the least amount of energy and their delivery rates are close to that of CAM as shown in Figure 12(d). Also, the comparison with PSM-16 shows that power management with traffic-aware optimization can save up to 80% of energy expended by PSM-16, while delivering the same number of messages.

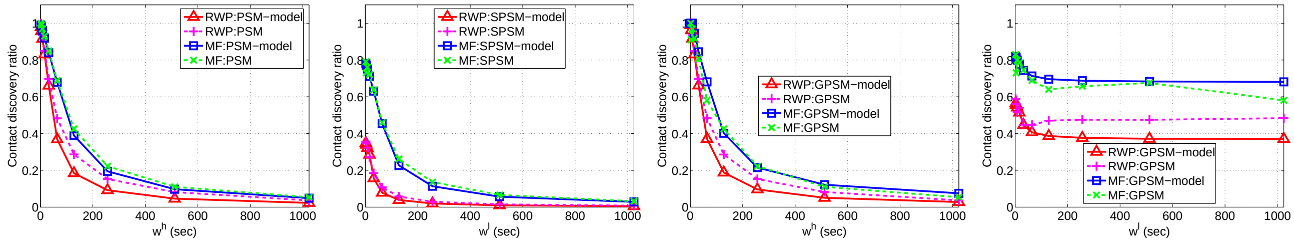
From this evaluation, we conclude the following. First, all of the techniques save considerable energy by utilizing the traffic-aware optimization. Secondly, the performance of each mechanism depends on the node mobility model: PSM works better when nodes pass by each other at long distances, and SPSM works better when nodes tend to meet at short distances. GPSM is flexible enough to adapt its behavior to both mobility scenarios and achieve the equivalent performance of the best performing power management scheme in each scenario. Third, traffic-aware optimization saves energy more efficiently than purely optimizing for discovery performance. However, in both mobility scenarios PSM achieved similar performance to GPSM, bringing into question the necessity of a second radio. As we have stated, the second radio is most useful in other mobility scenarios where the second radio is in range of other nodes most of the time.

6. RELATED WORK

Power management in wireless ad hoc networks has been studied in various aspects. First, measurement studies ([11, 29]) show that energy consumption while idling is as high as that while receiving data. Thus, nodes can save significant energy by disabling their radios (i.e., sleeping), if not used. Exploiting this idea, many sleep/wake-up cycling mechanisms have been proposed in multihop ad hoc network to save energy while keeping network connectivity ([1, 30, 36, 7, 31]). These approaches assume that a network is densely deployed, in which a node has another node within its radio range most of the time. Thus, they focus on how to overlap the time intervals in which nodes are awake to form a connected network, while allowing nodes to sleep. In our approach, we consider sparse networks in which nodes are often isolated from the rest of the network for a long time.

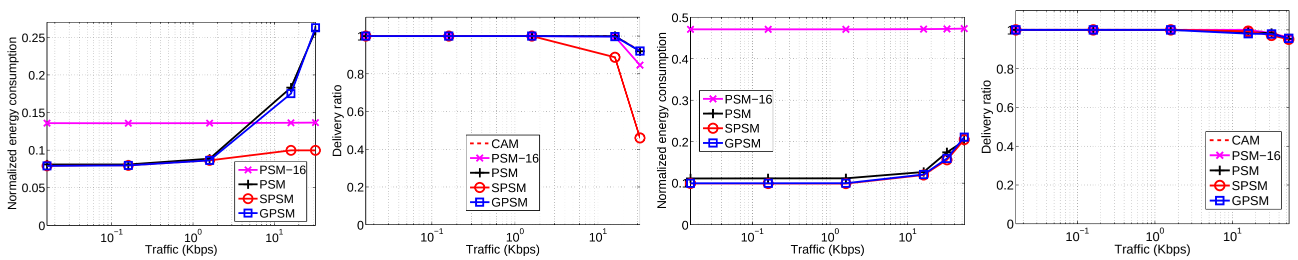
Secondly, a lot of efforts have been devoted to develop energy efficient Medium Access Control (MAC) protocols ([27, 32, 22, 9, 26]). These studies are initiated by observing that transmission of multiple nodes in wireless medium interfere with each other, so at most two nodes can communicate within a radio range at a time. Thus, if a node sleeps while others are communicating, it can save energy without sacrificing its throughput. Therefore, they propose mechanisms to increase sleeping time based on traffic activity in the neighborhood. As a consequence, they are useful in a dense network rather than in a sparse network such a DTN.

Third, hierarchical power management has been implemented in various forms ([25, 28, 21]). They utilize low power devices to lis-



(a) PSM (b) SPSM (c) GPSM(w^h) (d) GPSM(w^l)

Figure 11: The actual contact discovery ratio compared to the estimated contact discovery ratio for both scenarios, MF and RWP, when wake-up intervals vary. Figure 11(c) is drawn when w^l is 1024 seconds, and Figure 11(d) is drawn when w^h is 64 seconds.



(a) energy consumption (RWP) (b) delivery ratio (RWP) (c) energy consumption (MF) (d) delivery ratio (MF)

Figure 12: The impact of traffic-aware optimization to the power management in the RWP and MF scenarios

ten for incoming signals and to wake up the main device, if needed. Also, studies in [5, 2, 3] propose to use multiple radios to save energy by offloading data traffic in a low rate to a low power radio or to increase the capacity of a mesh network. However, all of them assume that nodes always close enough to other nodes. So, they did not investigate the impact of the short radio range of the low power devices to networking performance. In this paper, we explore the limitation using simulations and propose a framework to overcome the drawbacks.

Finally, energy can be saved by using mobile nodes [24, 19, 12]. Studies in [24] utilize mobile nodes to collect data from stationary sensors. They use short range radio and low duty cycle of sensors to save energy. Also, Jun et al. [19] use a mobile node, called ferry, to route messages even in a dense network and develop power management mechanisms for mobile nodes as well as stationary nodes, in which nodes alternate between sleeping and waking up according to the predicted location of the ferry. On the other hand, Goldenberg et al. propose to control node mobility to optimize the network performance such as energy efficiency based on specific traffic demands while using multihop routing protocols [12]. This approach requires nodes with extra capability to control their movement. In this paper, we assume that all nodes participate in routing and do not control node mobility.

7. CONCLUSIONS

In this paper, we investigate power management in DTNs with high randomness in the node mobility. We present a hierarchical power management framework, in which nodes maneuver two radio interfaces to discover contacts while saving energy. In addition, we provide traffic-aware optimization methods to save energy while discovering enough contacts to deliver the expected traffic load in the network. Our simulation results from two mobility models show that our generalized power management mechanism could achieve better energy efficiency than mechanisms relying only on one radio for contact discovery. In addition, our approximation algorithms help nodes to save significant amount of energy. Meanwhile, our results also show that while an additional low power radio does reduce the energy consumption needed for discovery, the improvement could be negligible in mobile DTNs.

It is our contention that power management is a critical issue in DTNs. This initial work opens several new problems in DTNs including: learning mobility patterns to help power management, using information from other nodes to discover more information about when to wake up, taking various levels of wake-up overhead into account, integrating a network with random mobility with a network with some degree of regularity, e.g., a bus network, utilizing multiple levels of radios to discover contacts or to offload traffic load among them, and exploring mobility models to assist efficient power management.

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