Twinkle: Network Power Scheduling in Sensor Networks

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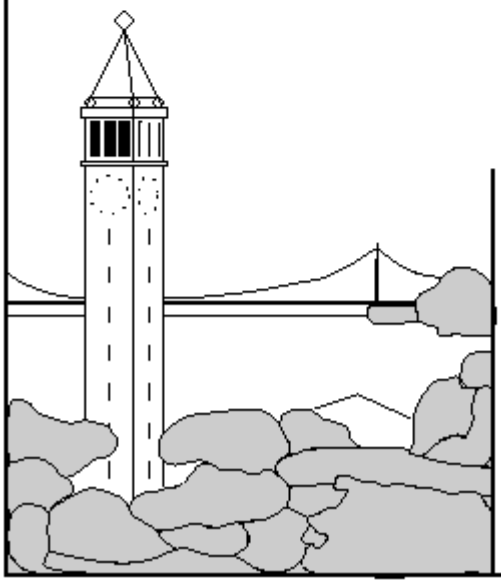

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We present our experience with Twinkle, the first implementation of network-layer power scheduling with real applications. Twinkle uses dynamically created schedules to schedule network flows in sensor networks. The scheduling allows nodes to turn off their radio when idle, thus saving power. Twinkle supports broadcast and partial flows for flexibility, and integrates time synchronization to enable scheduling to work on real motes. We show that it avoids contention, increases fairness, and that it can achieve power savings of 2-5x for real applications over existing power-management schemes, and over 150x compared with no power management. Finally, we discuss the extensions to the original algorithm needed for real applications.

1 Introduction

Power is one of the dominant problems in wireless sensor networks. Constraints imposed by the limited energy stores on individual nodes require planned use of resources, particularly the radio. Sensor network energy use tends to be particularly acute as deployments are left unattended for long periods of time, perhaps months or years.

Communication is the most costly task in terms of energy [Asad98,Dohe01,Sohr00,Pott00]. At the communication distances typical in sensor networks, listening for information on the radio channel is of a cost similar to transmission of data [Ragh02]. Worse, the energy cost for a node in idle mode is approximately the same as in receive mode. Therefore, protocols that assume receive and idle power are of little consequence are not suitable for sensor networks. Idle listening, the time spent listening while waiting to receive packets, comprises the most significant cost of radio communication. Even for hand-held devices Stemm et al. observed that idle listening dominated the energy costs [Stem97]. Thus, the biggest single action to save power is to turn the radio off during idle times.

Unfortunately, turning the radio off implies that you must know that the radio will be idle in advance, and the easiest way to do this is to have a schedule. An obvious approach is to use TDMA to turn the radio off at the MAC layer during idle slots. However, this requires tight time synchronization and typically hardware support.

Scheduling *flows* helps for multi-hop topologies, which play a significant role in wireless sensor networks. Pottie and Kaiser [Pott00] cover the many advantages of multi-hop, including reduced energy use and routing around obstructions. In multi-hop networks the farthest nodes have more chances to drop packets, and thus using only hop-by-hop decisions (rather than flows), as with any MAC-layer approach, tends to achieve lower bandwidth and less fairness.

In our previous work, we proposed flexible power scheduling (FPS), which performed network-level power scheduling at a coarse grain, and used a normal CSMA MAC layer underneath to resolve collisions due to imprecise scheduling or overhearing [Hohlt04]. However, the prototype FPS version had only microbenchmarks of the scheduling algorithm and no performance evaluation with real applications.

The contributions of this paper are two-fold: 1) we present evaluations from two real applications using *Twinkle*[1], our second-generation implementation of FPS, and 2) we present the extensions to FPS required to support real applications. These extensions include support for broadcast (to enable dynamic queries and two-way communication), network time synchronization, and in-network aggregation.

In particular, we show that scheduling really does reduce contention and increase fairness via two microbenchmarks, and then we provide an application-level evaluation of the power savings using two real applications: the Great Duck Island [Main02] deployment and a TinyDB application that collects data on Redwood trees [TinyDB02]. We also compare Twinkle with low-power listening, an alternative proposal for power savings. Our contributions include:

- The first implementation of network power scheduling that supports real applications.
- A 4x power savings for the Great Duck Island application.
- A 4.3x power savings for a 35-mote sensor network using TinyDB, compared with the default "duty cycling" power management scheme, and 150X versus no power management.
- A detailed comparison between Twinkle and Low-Power Listening with measured power data from real motes. This reveals a 2x or more power savings due to Twinkle.

1: The name "Twinkle" comes from observing the network: scheduling avoids collisions and thus the network twinkles if you turn on an LED every time a node transmits.

Section 2 presents an overview of the basic approach and the changes we made to make this approach realistic. Section 3 verifies the reduction in contention and improved fairness due to scheduling, and Sections 4 and 5 present evaluations using two real applications. Finally, Section 6 discussions some of the implementation details, Section 7 covers related work, we conclude in Section 8.

2 Twinkle Overview

Flexible power scheduling (FPS) [Hohlt04] introduced the approach of scheduling the network for power savings in sensor networks. The FPS protocol proposes a two-level architecture that combines coarse-grain scheduling at the network layer to plan radio on-off times, and simple CSMA to handle channel access at the MAC-layer. We outline the basic approach here and discuss the extensions we have added to further support real application requirements.

Power scheduling is primarily useful for low-bandwidth long-lived applications. The FPS scheme exploits the structure of a tree to build the schedule, which makes it useful primarily for data collection applications, rather than those with any-to-any communication patterns. We have added broadcast capability so that we can use the tree in both directions. Most existing applications fit this model, including equipment tracking, building-wide energy monitoring, habitat monitoring [Szew04, TASK05], conference-room reservations [Conn01], art museum monitoring [Sensicast], and automatic lawn sprinklers [DigSun].

The basic approach is to use a schedule that tells every node when to listen and when to transmit. As the bandwidth needs are low, most nodes are idle most of the time, and the radio can be turned off during these periods. Scheduling has two major requirements: the algorithm must be adaptive and decentralized.

The primary contribution of FPS was a distributed protocol for determining a schedule. The scheduling is *receiver initiated*. In particular, the schedule spreads from the root of the tree down to the leaves based on the required bandwidth: parents advertise available slots and children that need more bandwidth request a slot. Applied recursively, this allows bandwidth allocation for all of the nodes in the network. Although this schedule ensures that parents and their children are contention free, there may still be contention due to other nodes in the network or poor time synchronization; however, this contention is rare and can be handled by a normal CSMA MAC layer.

In FPS, reservations correspond to a unit flow from source-node to root, and thus the schedule is really a schedule of flows. Scheduling flows reduces contention and increases fairness (which we will show), and form one reason why higher-level scheduling has more value than traditional TDMA.

To allow adaptive schedules, advertising continues after the initial schedule is built. If new nodes arrive, or bandwidth demands change, children can request more bandwidth or release some.

Twinkle is our second-generation implementation of FPS with extensions added for application support. The basic radio power scheduling remains the same as the original FPS protocol. These four major extensions are:

Partial Flows: FPS only supports the reservation of entire flows from the network to the base station. Twinkle introduces partial flows. A partial flow is one that terminates at a node other than the root. For example, Twinkle's partial flows can be used to enable in-network aggregation, in which the flow terminates at the node that does the aggregation.

Broadcast: FPS does not support broadcast, which is a huge practical problem for systems like TinyDB that need to broadcast queries or parameters to control data collection. Broadcast uses partial flows in the reverse direction: each node reserves a partial flow with its parent that it will use as a broadcast channel for its children. At the time the reservation is made the node learns of its parent's broadcast channel.

Time Sync: FPS itself only requires coarse slot alignment to synchronize time slots. However, time synchronization is vital to sensor networks in general because it is needed to correlate sensor readings and debugging information after data has been extracted from the network. Tracking algorithms and location-based algorithms require time synchronization as well. This was not addressed by FPS and we present an efficient solution based on work from Vanderbilt [Maro04].

Latency Optimizations: The standard scheduling model of FPS has each flow reserving one slot per cycle for a given child-parent link. This can lead to high latency, since a flow makes only one hop of progress per cycle. Twinkle makes two important optimizations to reduce latency.

1. We order slots within a cycle so that the parent-grandparent slot occurs after the child-parent slot. This allows multiple hops per cycle.
2. We allow *fractional* reservation of slots, which enables one transmission every k cycles. This allows shorter cycle times without requiring more power, since a fractional slot reservation requires k times less power. Thus we can reduce latency by shortening the cycle time without increasing the required power.

We cover each of these contributions in more detail in Section 6, after we evaluate Twinkle via a microbenchmark and two applications.

3 Microbenchmarks

In this section we present two microbenchmarks conducted on `mica` motes; one on contention and one on fairness. Figure 1 shows 11 motes arranged in a 3-hop topology. For each experiment, 6 leaf nodes send

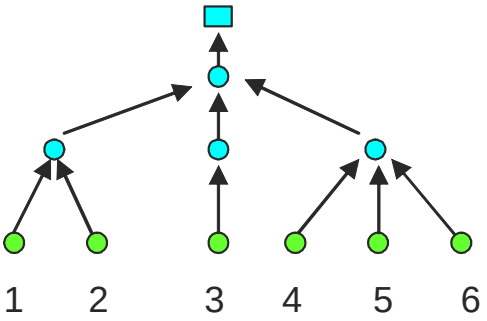

Figure 1: Topology used in mica experiments

100 messages at a rate of one message every 3.2 seconds. Each experiment is repeated 11 times.

3.1 Contention

An important part of network-layer scheduling is that it should reduce the contention seen at the MAC layer. There will still be some due to hidden terminals and imperfect time synchronization, but it should be greatly reduced.

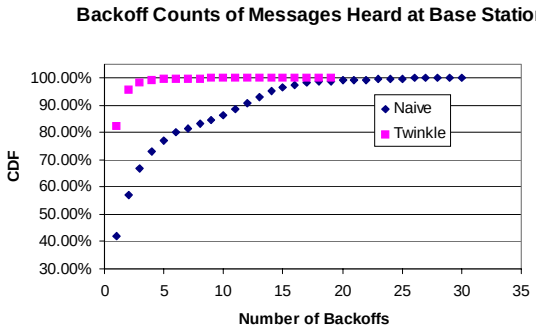

Figure 2: CDF of the number of backoffs due to contention with a normal "naive" application, and the same traffic using Twinkle. (Both use the same CSMA Mac.)

Figure 2 represents the the impact of 6 leaf nodes in a tree sending traffic to the root accross 3 hops. We compare one set of experiments that uses scheduled communication, Twinkle, with a second set that uses unscheduled communication, naive store-and-forward. The "naive" application simply sends that data at a fixed rate with no coordination beyond the MAC layer. The "Twinkle" version uses Twinkle to schedule the communication, but transmits at the same rate and the same amount of traffic, and uses the same underlying MAC layer. By counting backoffs as they occur and logging this data at the base station we can compute the CDF for backoffs for the whole network.

As shown, there is almost no contention with Twinkle, and extensive contention with the naive approach. This contention is due primarily to the interference between grandparents and children, and also to correlations in traffic due to the periodicity.

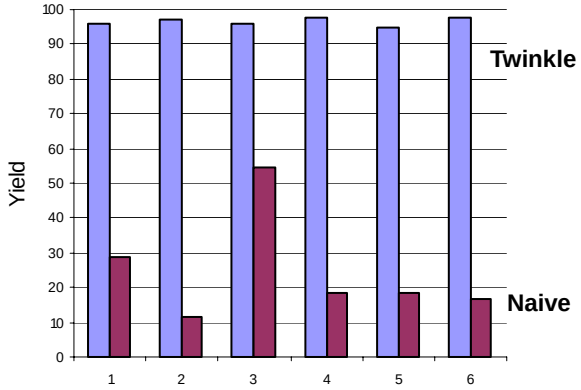

Figure 3: Thoughput (and thus fairness) for six motes that are three hops from the root.

3.2 Fairness and Throughput

Wireless links are inherently lossy and multi-hop wireless networks additionally suffer from end-to-end packet loss. *Yield*, the percentage of packets received at the destination out of those sent from the source, is often used to measure packet loss in multi-hop networks. Link-layer retransmission, adaptive rate control, and channel–switching are popular techniques for countering loss in wireless sensor networks. These methods operate at the link layer, and although effective, cannot detect or break end-to-end traffic correlations. A major source of contention is due to traffic flows interfering with themselves and with *other* traffic flows. We use yield as both a measure of throughput and end-to-end fairness among traffic flows. For all our experiments we use the standard TinyOS CSMA MAC with no retransmission, no rate control, and no channel switching, so that we may observe the actual effect Twinkle has on end-to-end fairness and throughput.

Figure 3 shows the percentage of messages received at the base station for Twinkle and Naive from a microbenchmark using the same setup as Section 3.1. The X-axis is the sending mote id and the Y-axis is the percentage of packets received at the base station, or yield. Note that in the Naive tests, mote 3 is only two hops from the base station (due to a hardware failure). This accounts for the higher yield and illustrates the difference in packet loss between 3 and 2 hops. The overall throughput is 96% for Twinkle versus only 25% for Naive (despite its advantage on mote 3)

Approach	Average	STDDEV	Max/Min
Twinkle	96.4	1.13	1.03
Naive	24.7	6.19*	2.4*

Table 1: Throughput and Fairness
* excludes mote 3 (see text)

To compare flows for fairness, we do not include mote 3 for Naive, since it only included two hops. One measure of fairness is just the standard deviation of the throughput across the flows, which is +/- 1.13% for Twinkle and +/- 6.2% for Naive. Thus, Twinkle has significantly less variation despite higher throughput. Second, we compute the ratio of the max and min throughputs; if the approach is fair this ratio should be small. For Twinkle, the ratio is only 1.03, versus about 2.5 for Naive (Table 1). We conclude that communication scheduling does indeed increase throughput and end-to-end fairness.

Finally, note that although we did not use link-layer retransmission or channel switching, we still achieved excellent end-to-end throughput. These techniques are largely complementary to Twinkle and can be used with Twinkle.

4 Application: Great Duck Island

Our first target application, GDI [Main02,Szew04], is a habitat monitoring application deployed on Great Duck Island, Maine. GDI is a sense-to-gateway application that sends periodic readings to a remote base station, which then logs the data to an Internet-accessible database. The architecture is tiered, consisting of two sensor patches, a transit network, and a remote base station. The transit network consists of three gateways and connects the two sensor patches to the remote base station. There are two classes of `mica2dot` hardware: the *burrow* mote and the *weather* mote. The burrow motes monitor the occupancy of birds in their underground burrows and the weather motes monitor the climate above the ground surface. In this section, we will draw on information about the *weather* motes provided by the study of the Great Duck Island deployment [Szew04].

Of the two weather mote sensor patches, one is a singlehop network and the other is a multihop network. The singlehop patch is deployed in an ellipse of length 57 meters and has 21 weather motes. Data is sampled and sent every 5 minutes. The multihop network is deployed in a 221 x 71 meter area and has 36 weather motes. Data is sampled and sent every 20 minutes.

In this section we compare the end-to-end packet reception, or *yield*, and power consumption of Twinkle/FPS with the low-power listening technique [Hill02] used at Great Duck Island. Both schemes will be running the GDI application on a 30 node laboratory testbed. We will additionally investigate the phenomena of *overhearing* in the low-power listening case.

4.1 GDI with Low-Power Listening

The GDI application uses low-power listening to reduce radio power consumption. In low-power listening, the radio periodically samples the wireless channel for incoming packets. If there is nothing to receive at each sample, the radio powers off, otherwise it wakes up from low-power listening mode to receive the incoming packet. Messages include very long preambles, so they are at least as long as the radio channel sampling interval. The advantages of low-power listening are that it reduces the cost of idle listening, integrates easily, and is complementary with other protocols. It is characterized by high end-to-end packet reception, or *yield*. This is due to the long packet preamble acting as an in-band busy-tone.

Density and multihop also impact power consumption. The GDI study [Szew04] reports a much higher power consumption in the multihop patch than the single hop patch which resulted in a shortened network lifetime — 63 of the 90 expected days — for the multihop patch. Two causes are attributed. First, messages have a higher transmission and reception cost due to their long preambles. Second, nodes wake up from low-power listening mode not only to receive their own packets, but anytime a packet is heard, regardless of the destination. *Overhearing* is the main contributor to the higher power consumption in the multihop patch.

We also observe that although low-power listening reduces the *cost* of idle listening it does not reduce the *amount* of idle listening, so that at very low data-sampling intervals its advantage declines because the radio must continue to turn on to check for incoming packets although there are none to receive. For very low data rates, we will show that scheduling such as Twinkle becomes more attractive because the radio (and potentially other subsystems) can be deterministically powered down until it is time to be used.

Lastly, we consulted with the principle architect of GDI [Szewczyk] in the analysis, correctness, and verification of our methodology.

4.2 GDI with Twinkle

We implemented a version of GDI in TinyOS [TinyOS00] that uses Twinkle for its radio power management. This was a rather straight forward integration that consisted of wiring the GDI application component to the Twinkle component and disabling low-power listening. The Vanderbilt TimeSync, SysTime, and SysAlarm [Maro04] components are used for time synchronization and timers. At the time of this work, TimeSync only supported the use of SysTime, which uses the CPU clock. The implication being, that for these experiments, GDI was not able to power manage the CPU. In all of our data presented here, we subtracted the draw of the CPU as if we had used a low-power Timer implementation. A version of TimeSync using the external crystal will become available shortly.

4.3 GDI Experiments

We conducted a total of 12 experiments on two versions of the GDI application. GDI-lpl uses low-power listening for radio power management and GDI-Twinkle uses Twinkle for radio power management The experiments were run on a 30-node in-lab multihop sensor network of `mica2dot` motes.

Twinkle supports data-gathering type applications like GDI where the majority of traffic is assumed to be low-rate, periodic, and traveling toward a base station. We ran a simple routing tree algorithm provided by

Twinkle based on grid locations to obtain a realistic multihop tree topology and then used the same tree topology for the 12 experiments. As is done in the Great Duck Island deployment, no retransmissions are used in these experiments.

In each experiment we varied the data sample rate: 30 seconds, 1 minute, 5 minute, and 20 minutes. For experiments with 30 second and 1 minute sample rates, 100 messages per node were transmitted. For experiments with 5 minute and 20 minute sample rates, 48 and 12 messages were transmitted per node respectively. In the GDI-lpl experiments we varied the channel sampling interval: 485 ms and 100 ms. All experiments collected node id, sequence number, routing tree parent, routing tree depth, node temperature, and node voltage. The GDI-Twinkle experiments additionally collected the number of children, number of reserved slots, current transmission slot, current cycle, and number of radio-on slots per sample period.

4.4 Measuring Power Consumption

During the experiments we measured the actual current of two nodes located in two separate places of interest in the network. One node, we call the *inner node*, is located one hop from the base station and has a heavy amount of route-through traffic that is similar to its routing one-hop siblings. This should give us an estimate of the maximum lifetime of the network. The other node is a *leaf node* that is one-hop from the base station as well. As it does not route-through any traffic, we should be able to see the effect of overhearing on power consumption at a node in a busy part of the network. If the measured current of the *inner node* and *leaf node* are similar in their active cycles, then we know the inner node is experiencing overhearing since all other factors remain the same.

At the lower sample rates, it is not feasible to take a measurement over the entire sample period, so we designed our experiments so that we could take some measurements and extrapolate others. For GDI-Twinkle, we define a cycle to be 30 seconds. Thus, a full sample periods for the 30-second, 1-minute, 5-minute, and 20-minute sample rates are 1, 2, 10, and 40 cycles respectively. We schedule all data traffic during one cycle of each sample period called the *active cycle*. The unscheduled cycles are called *passive cycles*. Both active and passive cycles include protocol traffic (i.e. sending advertisements and listening for requests). We then measure the current at the two motes capturing data from both active and passive cycles during the 1 minute sample rate experiment. Then we take a running windowed average over a full 1-minute period, which gives us the power draw for both an active and passive cycle. Table 2 presents these direct power measurements.

For GDI-lpl we follow a similar method. We measure current at the two motes capturing data from both active and passive periods during the 1-minute sample period experiment. To represent an active period, we take a running average over the full 1-minute period. This also captures all the overhearing that occurs at the mote during a full period of any given sample rate. To represent a passive period, we took the longest chain of data from the measurements in which only idle channel sampling occurred. From this information we calculate the power consumption for the 5-minute and 20-minute sample rate experiments. The 30-second sample rate was measured separately (not calculated) and is shown in Figure 2.

4.5 Evaluation

In this section we discuss the results of the data from all 12 experiments, and we also compare with the actual GDI deployment data.

4.5.1 Power Comparison with Low-Power Listening

Given the direct power measurements from Table 1, we can estimate the power consumption for the 5-minute and 20-minute sample rate experiments. For example, for Twinkle, we read off the following: an active cycle at the inner mote consumes 2.18 mW and a passive cycle consumes 0.33 mW. Given these numbers, for a 20-minute sampling rate we expect 1 active cycle and 39 passive cycles, for a weighted average of 0.38 mW. For the leaf mote, an active cycle consumes 0.69 mW and a passive cycle consumes 0.33 mW, giving a weighted average of 0.34 mW.

Similarly, to compute the GDI-lpl power consumption at a 20-minute sample rate we assume that for one minute the application consumes the energy of the active period and for the remaining 19 minutes the application consumes the energy of the passive period. Using the values from Table 2, the inner mote during the 20-minute sample rate Lpl-100 experiment, would consume an average of 4.12 mW ((8.2+19*3.9)/20 = 4.12mW).

Figure 4 shows all four sample periods: the 30-second and 1-minute rates are measured, and the 5-minute and 20-minute periods are estimated as above.

For Twinkle, the inner node consistently has a greater draw than the leaf node. In contrast, for LPL, the

Power Management	Period (Sec)	Inner (mW)	Leaf (mW)
Twinkle active	30	2.18	0.69
Twinkle passive	30	0.33	0.33
Lpl-485 active	60	16.5	16.0
Lpl-485 passive	60	0.99	0.99
Lpl-100 active	60	8.20	7.60
Lpl-100 passive	60	3.90	3.90

Table 2: Power Measurement (mW)

inner and leaf nodes consistently have almost the same draw. This indicates that Twinkle's main power draw depends on the *routed traffic*, and in most of the cases LPL's main power draw depends on the *overheard* traffic. However, from Table 2 we see the passive power draw for LPL-100 is 3.9 mW, which forms an asymptote as the sample period increases. Overall, as the sample rate gets lower and the preambles get shorter, overhearing does not play as big role.

The next thing to notice is at the higher sample rates, LPL-485 has a higher power consumption than LPL-100, but at the lower sample rates, LPL-485 has a lower power consumption than LPL-100. This reveals a relationship within LPL where as the cost of transmitting increases with longer preambles, the cost of channel sampling decreases with longer sampling intervals.

Finally, we added a newer variation of LPL to the figure, called Pulse. Pulse was developed as part of BMAC [Pola04], and it optimizes the power consumption of LPL by listening for energy in the channel rather than a decoded preamble. This reduces the cost of listening substantially. We can compute the active and passive estimates for Pulse given our power traces and Table 2 from the BMAC paper, which provides the raw listening cost. Although Pulse does perform better than LPL, it is still 2x to 5x higher power consumption than Twinkle.

Across the board, Twinkle has better power consumption than LPL, with improvements that range from 2x (over Pulse for low rates) to 10x (in cases where the listening interval is poorly chosen).

4.5.2 Yield and Fairness

Table 3 shows the average yield (end-to-end packet reception) for all 12 experiments, and the ratio of the best and worst throughputs (Max/Min). This ratio indicates fairness: lower ratios are more fair.

At 30 seconds, the LPL-485 network is saturated due to the long preambles and this accounts for its low yield.

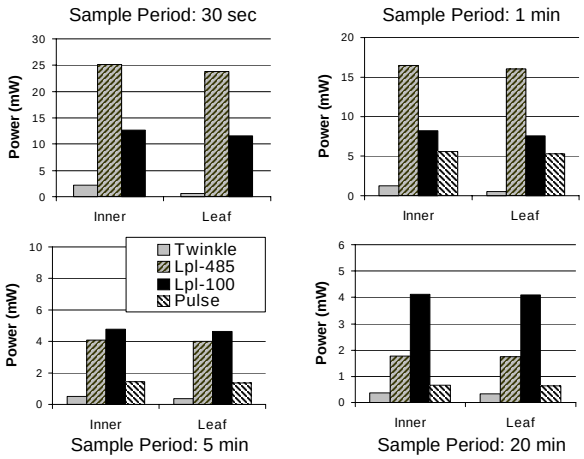

Figure 4: Relative power consumption of Twinkle and LPL for four different sample periods. Pulse is a newer version of LPL discussed below.

Power Scheme	Sample Period	Yield	Max/ Min
Twinkle	0.5	0.80	2.11
Twinkle	1	0.90	1.74
Twinkle	5	0.84	1.92
Twinkle	20	0.83	2.4
Lpl-485	0.5	0.40	15.6
Lpl-485	1	0.68	94.0
Lpl-485	5	0.72	11.8
Lpl-485	20	0.69	12.0
Lpl-100	0.5	0.85	3.45
Lpl-100	1	0.83	2.23
Lpl-100	5	0.78	2.76
Lpl-100	20	0.77	4.00

Table 3: Yield and Fairness Comparison

Overall, both Twinkle and LPL-100 are significantly better than LPL-485. Twinkle shows better fairness than LPL-100 and, other than the 30 second sample rate, Twinkle has higher yield than LPL-100.

4.5.3 Understanding the GDI Field Study

Viewing the data in comparison to the data provided by the GDI study [Szew04], we find the results in the laboratory are remarkably close to the results in the field.

The Great Duck Island deployment used a low-power listening channel sampling interval of 485 ms, a data sample period of 20 minutes in the multihop patch, and a data sample period of 5 minutes in the singlehop patch.

Table 6 presents results taken from the GDI field study, labeled GDI-485, and includes data from four of our in-lab experiments, labeled LPL-485 and Twinkle. For each row, we report the sample period, average yield, inner and leaf power consumption, and the number of nodes in the experiment. *For GDI-485, the yield figure represents the average yield from the first day of deployment.*

A close comparison can be drawn between LPL-485 and GDI-485 at the 20 minute sample rate. LPL-485 has a power draw of ~1.76 mW while GDI-485 has a power draw of 1.6 mW. The GDI-485 figure is expected to be lower for two reasons: in the laboratory, the two measured nodes are from the busier section of the testbed,

Power Mgnt	**Sample Period**	**Yield**	**Inner (mW)**	**Leaf (mW)**	#
GDI-485 (single)	5	0.70	n/a	0.71	21
GDI-485 (multi)	20	0.70	1.60	n/a	36
Lpl-485	5	0.72	4.09	3.99	30
Lpl-485	20	0.69	1.77	1.74	30
Twinkle	5	0.84	0.52	0.36	30
Twinkle	20	0.83	0.38	0.34	30

Table 6: Comparison of our lab data with the actual GDI field study

and the testbed has a constant load rather than a decreasing one. In the GDI deployment, some multihop motes died and stopped sourcing traffic, which is why we report yield from the first day of deployment.

The yield data is extremely close as well. All yields for LPL-485 and GDI-485 are ~70%. The only large difference between the two data sets is the power consumption at the 5-minute sample period. This is easily explained by recalling that at the 5-minute sample period, GDI-485 is singlehop while LPL-485 is multihop, and the LPL-485 measurements include a large amount of overhearing.

The closeness of the LPL-485 and GDI-485 data gives us high confidence in the corrrectness of our methodology and the results of our laboratory experiments. We expect the Twinkle numbers are a good estimate of how Twinkle would do were we to have access to a field deployment. Our laboratory experiments show that Twinkle consumes at least 4x less power and provides about 14% better yield.

5 Application: Redwoods with TinyDB

Our second target application, TinyDB [TinyDB02], is a distributed query processor for TinyOS motes. TinyDB consists of a declarative SQL-like query language, a virtual database table, and a Java API for issuing queries and collecting results.

Conceptually the entire network is viewed as a single table called *sensors* where the attributes are inputs of the motes (e.g., temperature, light). Queries are issued against the *sensors* table via the Java API and disseminated throughout the network. The SQL language is extended to include an "`EPOCH DURATION`" clause that specifies the sample rate. A typical query looks like this:

```
SELECT nodeid, temperature
FROM sensors
EPOCH DURATION 3 min
```

TinyDB allows up to two queries running concurrently: one for sensor readings and one for network monitoring. In theory, TinyDB can support multiple concurrently running queries, however, the current strategy for duty cycling and synchronization of sensor data readings has had implications for what is actually feasible. To FPS, queries in general are viewed as increases or decreases in demand. The notion of why a change in demand occurs (e.g. whether it is one or more queries) is transparent to FPS. This makes TinyDB an ideal target application for Twinkle.

In this section we compare the power savings of TinyDB using Twinkle versus TinyDB using application level duty cycling — the power management scheme currently used in TinyDB. We estimate the power savings of the two approaches using the TinyDB Redwood deployment in the Berkeley Botanical Garden [BotGar04] as our topology and traffic model.

5.1 Estimating Power Consumption

As it is not feasable to directly measure the power consumption of 35 motes, we use the following three-part methodology:

1. Estimate the amount of time the radio is on and off for each scheme. Our metric for this will be radio on time per hour, measured in seconds.
2. For Twinkle, we validate this estimate in Section 5.5 by looking in detail at one of the motes. The radio on time for duty cycling is easy to estimate.
3. We use actual measured current from `mica` and `mica2` motes to estimate power consumption from radio on/off times. (In the GDI application we measured the current directly during the experiment.)

This combination provides a reasonably accurate overall view of power consumption, which although not perfect is certainly very accurate relative to the 5x (Section 5.4) advantage in power shown by Twinkle.

Lastly, we consulted with the principle architect of TinyDB [Madden] on analysis, correctness, and verification of our methodology.

5.2 Topology and Traffic Model

The Redwood deployment has 35 mica2dot motes dispersed across two trees reporting to one base station in the Berkeley Botanical Gardens. Each tree has 3 tiers of 5 nodes each and 2 nodes placed at each crest. One tree has 1 additional node at a bottom branch. Every 2.5 minutes each mote transmits its query results, which are multi-hopped and logged at the base station.

The routing scheme uses link estimation to parent switch, so the topology changes over time. By examining the records in the redwood database, we derived the actual topology information. From this, a general topology was constructed that reflects its state the majority of the time.

Out of 35 nodes, generally 2/3 of the nodes are one hop from the base station and 1/3 of the nodes are two hops from the base station at any given time. We start by computing the radio on time per hour for the case with no power management:

```
60 sec/min * 60 min/hour = 3600 sec/hour
```

No power management = 3600 sec/hour

This number is the average amount of time each radio is on per hour for the whole deployment. We next estimate this metric for duty cycling followd by an estimate for FPS.

5.3 Duty Cycling

In TinyDB duty cycling, the default power management scheme, all nodes wake up at the same time for a fixed waking period every EPOCH. During the waking period nodes exchange messages and take sensor readings. Outside the waking period the processor, radio, and sensors are powered down. Estimating the radio-on time is thus straightforward: all 35 nodes wake up at the same time every 2.5 minutes for 4 seconds and exchange messages. The sample rate is thus 24 samples per hour. Each node is on for 96 sec/hour.

```
24 samples/hour * 4 sec/sample = 96 sec/hour
```

Duty Cycling = 96 sec/hour

As expected, this approach is subject to very high packet losses due to the contention produced by exchanging packets at nearly the same time. A recent TinyDB empirical study [TASK05] shows high losses, between 43% and 50%, and high variance using duty cycling. Although we did not test it explicitly, there is no reason to expect the yield for Twinkle (or low-power listening) would deviate from the 80% shown in the previous section.

5.4 Twinkle

Topology, time-slot duration, protocol traffic, and data traffic are factors in estimating the radio-on time for Twinkle. We will use the same topology as above for estimating the radio-on time of the 35 nodes. Time-slot duration and number of slots per cycle are configuration parameters in Twinkle. For this example, the time slot duration is 128 ms and there are 1172 slots per cycle, which is roughly 2.5 minutes. The advertising frequency is once per cycle.

Figure 5 depicts our subtree topology and traffic model. Solid lines represent data traffic (T/R) that is forwarded from the network to the base station every cycle. Dashed lines represent a Broadcast channel used for protocol traffic (B/RB). The Broadcast channel is used for TinyDB queries and network protocol messages.

Given the topology and traffic we can now calculate the radio-on time for each node. Node 0 is the base station

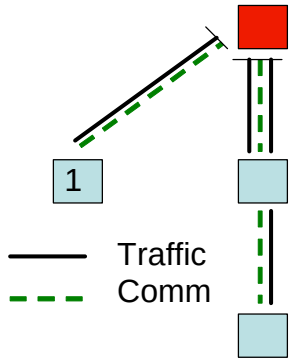

Figure 5: Topology and Traffic for Estimates

and has no cost. There is an additional cost of 3 time slots per cycle to do an adaptive advertisement (A) once per cycle: one advertisement and 2 receive pending.

Node	T	R	B	RB	A
1	1	0	1	0	3
2	2	1	1	1	3
3	1	0	1	0	3

Table 7: Traffic per Cycle (number of time slots)

For each node the cost is 0.767 seconds per cycle:

```
5(T/R) + 4(B/RB)+ 9(A)
= 18 * 128ms
= 2.3 sec/cycle per 3 nodes
= 0.767 sec/cycle (per node)
```

At 24 samples per hour, on average, each node is on 18.4 sec/hour:

```
24 samples/hour * 0.767 sec/cycle
= 18.4 sec/hour
```

Twinkle = 18.4sec/hour

This is a savings of 5.2x compared with the duty cycle approach and 196x compared with no power management. In addition, the radio-on time is actually overestimated. Transmit slots do not leave the radio on for the whole slot since they can stop once their message is sent; this is shown in detail in the next section.

5.5 Twinkle Validation

We implemented a prototype of TinyDB that uses Twinkle for radio power management. To validate our prototype, we ran the following experiment on three `mica2dot` motes and one `mica2` mote as base station arranged in a topology shown in Figure 5. We monitored intermediate Node 2 while it forwarded packets and sent advertisements once per cycle. There are 64 slots of 128 ms each per cycle. We instrumented TinyDB-Twinkle to

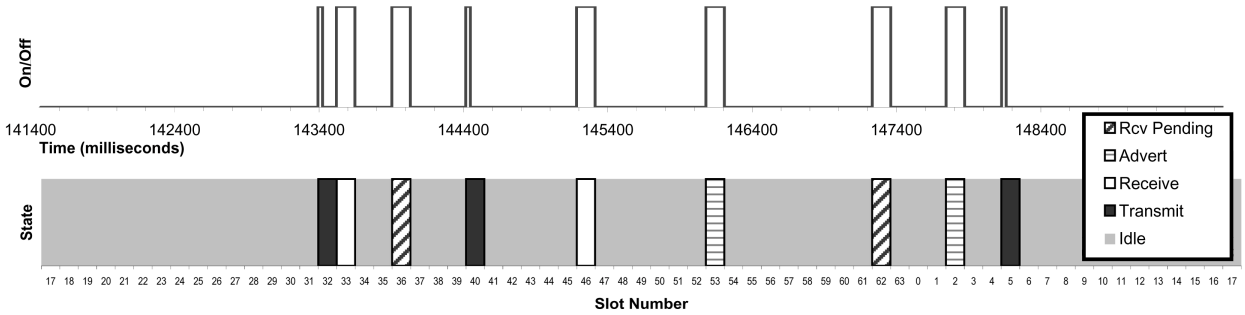

Figure 6: A subsection of the validation experiment. The bottom graph shows the measured Twinkle state versus time and the slot number; this section shows about one cycle with 64 slots per cycle and 128ms slots. The top graph shows actual radio on/off times. Note that the radio is always off for Idle cycles and that for Transmit cycles the on time is just long enough to transmit the queued messages.

record the time of each call to turn the radio on and radio off, the beginning time of each time slot, and the state of each slot. From the TinyDB Java tool we issue the query:

```
SELECT nodeid
FROM sensors
EPOCH DURATION 8192 ms
```

The intermediate mote is connected to an Ethernet device, and the debug records are logged over the network to a file on the PC. The regular query results are multi-hopped to the base station and displayed by the Java tool.

In this experiment, we expect to have 1 advertisement, 2 receive pending slots, 3 transmit slots (one is a broadcast), 2 receive slots, and 56 idle slots per 64-slot cycle. We validated both the use of slots and the radio on/off times:

Metric	Slots	Idle %
Predicted Idle Slots	56/64	89.1%
Measured Idle Slots	56/64	89.1%
Measured Radio Off Time	—	91%

Note that the radio off time is higher than the percentage of idle slots because Transmit slots turn the radio off early — as soon as their messages have been sent.

Figure 6 shows a subsection of the validation experiment. The bottom graph shows the measured Twinkle state versus time and the slot number; this section shows the active portion of a cycle (slots not shown are idle). The top graph shows actual radio on/off times (milliseconds). Note that the radio is always off for Idle slots and that for Transmit slots the on time is just long enough to transmit the queued messages. In this experiment, the time slot duration is 128 ms, there are 64 slots per cycle, and the advertising frequency is once per cycle. This cut shows two adaptive advertising slots, which is fine given that they are actually in two different cycles.

This experiment validates our methodology and shows that the power estimate for Twinkle in the previous section is actually conservative (since we count all of the Transmit slot time).

Mote	Asleep	CPU	CPU+Radio
Mica1	0.01	0.4	8.0
Mica2	0.03	3.9	20

Table 8: Power Consumption of Motes (mA)

Scheme	Radio On Time	Ratio
None	3600	196
Duty Cycling	96	5.2
Twinkle	18.4	1

Table 9: On Times (seconds per hour)

5.6 Power Savings

Finally, given the validated radio on times, we can estimate the power savings. First, however we need to know the current draw for a mote depending on whether or not the radio is on, and/or the CPU is on. We obtained the results shown in Table 8 via an oscilloscope tracing the motes during our experiments.[2] Given these current draws, we estimate power consumption as:

```
Power (mAh) = (On time)*(On draw)
            + (Off time)*(Off draw)
```

Using this equation and the radio-on times summarized in Table 9, we estimate the power consumption in Figure 7.

In all cases, both Duty Cycling and Twinkle perform substantially better (lower power) than no power management, so we focus on the difference between Twinkle and Duty Cycling.

The biggest issue for estimating the power savings is whether or not the CPU is asleep when the radio is off. Neither system needs the CPU per se during idle times, but some sensors may require CPU power. Thus we

2: `Mica2` radio power varies from 7.4 to 15.8 mA depending on transmit power, plus 7.8 mA for the *active* CPU draw for a total of 15.2 to 23.6 mA. We use 20mA as an overall estimate.

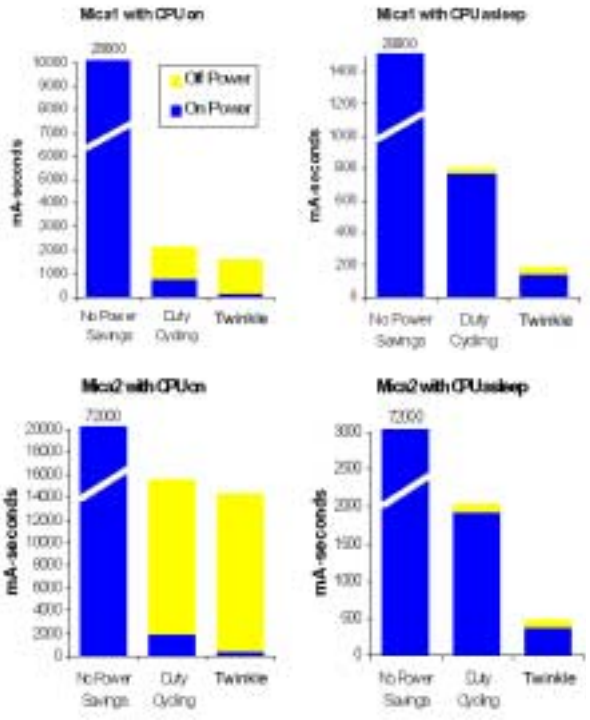

Figure 7: Estimating power savings for two families of motes (Mica1, top, and Mica2, bottom), with the CPU on or asleep when the radio is off. Each vertical axis has a different scale, and in all cases the "No power savings" column goes off the top (with the value shown). Light gray is the off power consumed (per hour), while dark gray is the on power.

expect for both the `mica1` and `mica2` the "CPU asleep" numbers are more realistic and we will quote these in our overall conclusions. However, we include the "CPU on" case for completeness. Note that even for cases where the CPU is needed for sensor sampling, the "CPU asleep" graph is more accurate, since the CPU would be asleep most of the time.

For the CPU on case, Twinkle outperforms Duty Cycling by 37% on the `mica1` and 8% on the `mica2`, which has a higher CPU current draw. Compared to no power management, the advantage for Twinkle is 18X and 5X respectively.

For the more realistic "CPU asleep" case, i.e. the CPU is asleep during Idle slots, Twinkle outperforms Duty Cycling by 4.4X on the `Mica1` and 4.3X on the `Mica2`. Note that this is consistent with the 5.2X reduction in radio on time. Compared to no power management, the advantage for Twinkle is 160X and 150X respectively.

Thus to summarize, for the TinyDB application with the Redwood study workload, we see a power savings of about 4.3X over Duty Cycling and 150X over no power management.

6 Discussion

In this section, we cover some of the details of Twinkle, including the key elements to support real applications.

6.1 Partial Flows and Broadcast

Twinkle proposes a new reservation type called *partial flows*. A partial flow is one that terminates at some node other than the root, i.e. the reservation is not from source to sink. Partial flows can be used to support various operations such as data aggregation, data compression, and query dissemination.

A broadcast channel is an instance of a partial flow. In Twinkle, upon joining the network, each node acquires at least one partial flow reservation that terminates at its parent. This is called the Comm channel and is used by the node as a broadcast channel for sending synchronization packets and forwarding messages injected from the base station. Twinkle protocol messages always include the slot number of the Comm channel. In this way, children nodes know in which slot to listen for broadcasts from their parent.

Twinkle maintains two forwarding queues: one for forwarding commands away from the base station and one for forwarding packets toward the base station. When a node receives a command message it invokes the appropriate command handler and places the message on the command queue for forwarding. The Comm channel is shared; both injected commands and synchronization packets use the same channel. The convention is if there is a command to be forwarded that is sent first followed by the time sync packet.

```
if current slot == Comm slot
    if command in command queue
     broadcast command message
    endif
    broadcast sync packet
endif
```

The GDI application in Section 4 used the Comm channel for time sync packets and injecting commands to start and stop the experiments. The TinyDB application in Section 5 used the Comm channel for time sync packet and injecting TinyDB queries.

6.2 Time Synchronization

The FPS protocol itself only requires coarse synchronization of time slots. Many applications, however, require a notion of global time to correlate sensor readings or debugging information. Others require precise time synchronization for their tracking and localization algorithms. Therefore we have added support for time synchronization in Twinkle.

We chose to integrate the Flooding Time Synchronization Protocol (FTSP) [Maro04] with Twinkle. The FTSP approach combines MAC layer timestamping with skew compensation. In collaboration with the FTSP developers we added two interfaces to FTSP:

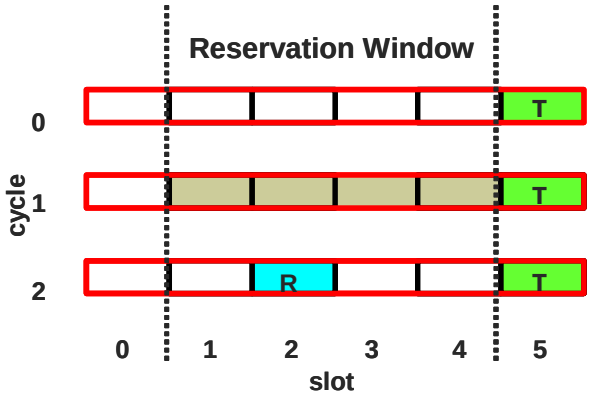

Figure 8: Reservation Windows

`TimeSyncMode` and `TimeSyncNotify`. `TimeSyncMode` allows Twinkle to explicitly schedule time sync messages. `TimeSyncNotify` allows Twinkle to know when time sync messages have been sent and received by FTSP. Twinkle schedules time sync messages during the Comm channel as discussed in the previous section.

We found FTSP worked very well with Twinkle. For `mica2dot` and `mica2`, FTSP yields a 1 microsecond per hop accuracy in a connected multihop network. The FTSP time stamping alone has an average error of 25 microseconds with a maximum error of 50 microseconds.

6.3 Latency Optimizations

Any scheduling scheme will impose larger per hop latencies than those that store and immediately forward. If scheduling is done per slot per cycle, as in FPS, then assuming messages are forwarded in FIFO order, it can take up to the time of an entire cycle to forward a packet to the next hop. If cycles are very large, then this may impose too much latency for some applications.

Twinkle improves on per hop latency by proposing two scheduling optimizations;

1. Reservation Windows
2. Fractional Flows

6.3.1 Reservation Windows

We observe that FPS employs *receiver initiated scheduling*. That is to say the selection and assignment of reservations slots is always made from the perspective of the receiving (route-through) node. We outline the steps to make a reservation below.

1. Parent selects an idle slot and advertises the slot.
2. Child hears the advertisements and sends a request for the slot.
3. Parent receives the request and sends an acknowledgement.

Here the parent node is the route-through node, closest to the base station. In Step 1, FPS selects an idle slot at random from its entire cycle of slots. As a latency optimization, Twinkle makes a simple modification to the protocol. Instead of selecting the slot from the entire cycle, Twinkle selects the slot from a subset called *reservation window.*

Given a cycle length of size `m`, the reservation window is a sliding window whose size is `w` where `w <= m`. The window begins `w` slots *prior to the last transmit slot* that the parent node reserved with its parent (the grandparent). In this way, using only local information, the slot being advertised to the child is always within `w` of the slot where it will be forwarded - putting an upper bound on the per hop latency of the network.

Other than `w <= m`, Twinkle does not restrict the value of `w` or whether it should be a fixed global value or an adaptive local value. For example, Twinkle might be extended to support some types of soft Quality of Service requirements by including the value of `w` in protocol messages.

Figure 8 shows 3 cycles of the schedule of a parent node that is scheduling some route-through traffic. Here the reservation window `w = 4`. In Cycle 0, the last *transmit* slot was scheduled at slot 5, and since `w = 4`, the next *receive* slot will be selected from between slots 1 and 4 in Cycle 1.

6.3.2 Fractional Flows

Fractional flows are a simple but useful optimization. Instead of giving a node one slot every cycle, a node may instead use the slot once every `k` cycles, which allows for very infrequent slots without the need for long cycles.

Conversely, this is also a latency optimization. An application designer can reduce latency by decreasing the cycle time, since this will reduce the delays in a multihop network. Without fractional flows, such a decrease implies an increase in power, since a node is sending more often. With fractional flows, the designer can changes some nodes to fractional slots to maintain a consistent power profile as the cycle time decreases. Combined with reservation windows, which coordinate the schedule, fractional flows allow fine-grain control over the tradeoff between latency and power savings.

7 Related Work

Power consumption is an important issue in wireless sensor networks. Energy optimizations must be considered throughout all layers of the hardware and software architecture. Energy issues for sensor networks are explored in [Dohe01,Pott00,Ragh02]. These works make clear that communication is the most costly task in terms of energy on the wireless node.

Many researchers are investigating software solutions to reduce communication costs. There is ongoing research in the areas of energy efficient channel access, routing, topology management, and in-network processing.

We based Twinkle on our previous FPS work at Berkeley [Hohlt04]. We made many changes to support real

application, the largest of which are discussed in Section 6 (and Section 2).

In the area of energy-efficient MAC layers, there are two broad classes of approaches: contention based [Pamas98,SMAC02,Dam03] and TDMA based [Sohr99,Aris02,Conn03]. PAMAS [Pamas98] enhances the MACA protocol with the addition of a signaling channel. It powers down the radio when it hears transmissions over the data channel or receptions over the signaling channel. S-MAC [SMAC02] incorporates periodic listen/sleep cycles of fixed sizes similar to 802.11 PS mode. In order to communicate, neighboring nodes periodically exchange their listen schedules. In the listen phase nodes transmit RTS/CTS packets and in the sleep phase nodes either transmit data or sleep if there is no data to send. T-MAC [Dam03] is a variation on S-MAC. Instead of using a fixed listen window size, it transmits all messages in bursts of variable length, and sleeps between bursts.

Although Twinkle is not a MAC protocol, we draw our inspiration from the TDMA-based energy-aware solutions. TDMA based protocols have natural idle times built into their schedules where the radio can be powered down. Additionally they do not have to keep the radio on to detect contention and avoid collisions. Centralized energy management [Aris02] uses cluster-heads to manage CPU and radio consumption within a cluster. Centralized solutions usually do not scale well because inter-cluster communication and interference is hard to manage. Self organization [Sohr99] is non-hierarchical and avoids clusters altogether. It has a notion of super frames similar to TDMA frames for time schedules and requires a radio with multiple frequencies. It assumes a stationary network and generates static schedules. This scheme has less than optimal bandwidth allocation. Slot reservations can only be used by the node that has the reservation. Other nodes cannot reuse the slot reservation.

ReOrgReSync[Conn03] uses a combination of topology management (ReOrg) and channel access (ReSync) and relies on a backbone for connectivity. Relay Organization is a topology management protocol which systematically shifts the network's routing burden to energy-rich nodes (wall powered and battery powered nodes). Relay Synchronization (ReSync), is a TDMA-like protocol that divides time into epochs. Nodes periodically broadcast small intent messages at a fixed time which indicate when they will send the next data message. All neighbors listen during each others intent message times. It assumes a low data rate and only one message per epoch can be sent.

Energy-efficient routing in wireless ad-hoc networks has been explored by many authors, see [Roye99,Yu01,Karp00,Haas02] for examples. Topology management approaches exploit redundancy to conserve energy in high-density networks. Redundant nodes from a routing perspective are detected and deactivated. Examples of these approaches are GAF [GAF01] and SPAN [SPAN01]. Our approach does not seek to find minimum routes or redundancy.

These protocols are designed for systems that require much more general communication throughout the network.

8 Conclusions

We demonstrated that Twinkle can save 2-5x of the power consumption for real applications that already use power management of some kind. We saw a 2-4x improvement for the GDI application, and about 4x for the TinyDB Redwoods deployment. We also covered several important enhancements to the idea of network-layer power scheduling to make it a realistic alternative for real deployments, including integration of time sync, support for broadcast and aggregation, and latency optimizations.

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