

Research Article

Dual Wake-up Low Power Listening for Duty Cycled Wireless Sensor Networks

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Energy management is an interesting research area for wireless sensor networks. Relevant duty cycling (or sleep scheduling) algorithm has been actively studied at MAC, routing, and application levels. Low power listening (LPL) MAC is one of effective duty cycling techniques. This paper proposes a novel approach called dual wake-up LPL (DW-LPL). Existing LPL scheme uses a preamble detection method for both broadcast and unicast, thus suffers from severe overhearing problem at unicast transmission. DW-LPL uses a different wake-up method for unicast while using LPL-like method for broadcast; DW-LPL introduces a receiver-initiated method in which a sender waits a signal from receiver to start unicast transmission, which incurs some signaling overhead but supports flexible adaptive listening as well as overhearing removal effect. Through analysis and Mote (Telosb) experiment, we show that DW-LPL provides more energy saving than LPL and our adaptive listening scheme is effective for energy conservation in practical network topologies and traffic patterns.

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1. INTRODUCTION

Energy conservation has been actively studied for wireless sensor networks [1, 2]. Among the diverse sources consuming energy in wireless sensor devices, the idle listening of radio transceiver has been known as a dominant component because radio circuitry relatively devours more power than other sources such as sensing circuit boards. In order to reduce such an idle listening, each sensor node goes into sleep state during idle time and its radio transceiver needs to be turned on at packet reception time. Thus, the idle listening problem can be regarded as how sender cost-effectively wakes up a sleeping receiver at the right time to enable seamless packet transmission.

For ultra-low power consumption, duty cycling technique has been introduced [3]. In duty cycled networks, each node periodically wakes up and sleeps according to its duty cycle. In TDMA-based sensor networks, implementing duty cycling is relatively easy because all nodes were synchronized over time slots; each node can listen only in assigned time slots and sleep in other time slots. However, as indicated in Hybrid Z-MAC [4], TDMA is hard to be fully used in ad-hoc sensor networks due to its global synchronization overhead.

Thus, its use has been limited to a special region like around sink nodes. By this reason, most clever duty cycling schemes have been devised for CSMA-based sensor networks.

In CSMA-based sensor networks [5], sender needs to make a duty cycled receiver ready to listen at packet transmission time. There are two rendezvous approaches, *synchronized listening* (SL) and *low power listening* (LPL). In SL approach, nodes are synchronized over time so each sender can transmit a packet to an intended receiver during synchronized listening period. S-MAC [6], T-MAC [7], and SCP-MAC [8] schemes are based on this synchronous approach. These schemes can provide low duty cycle performance but the need of time synchronization among nodes could be a drawback in terms of supporting network scalability and robustness.

In LPL approach, on the other hand, each node wakes up asynchronously at a given check interval. When a node awakes, it does check the channel state by performing a kind of clear channel assessment (CCA). Based on the fact that all nodes wake up at least once in the given check interval, sender first transmits a long preamble sized to the check interval before transmitting a data packet. The long preamble is used to make all neighbor nodes ready to receive the data

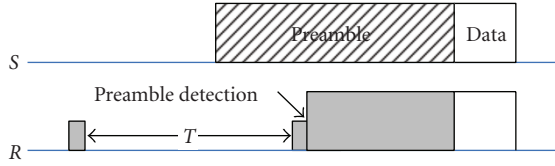


FIGURE 1: Low power listening- (LPL)-based on preamble sampling.

packet, as shown in Figure 1. At wake-up time of each node, if it detects a preamble on channel, it continues to listen until the transmission finishes. Otherwise, it goes back into sleep mode. This asynchronous approach can be favored with simple preamble sampling because it does not require any synchronization among nodes.

However, there are some inherent problems in LPL (a.k.a. B-MAC [9]) using preamble sampling. First main problem is a long preamble always accompanying with all data packets that causing excessive energy consumption in sender side, and second critical thing is an overhearing problem of non-intended receivers. The long preamble is inevitably detected by all neighbor nodes and such simple preamble detection is not enough to let the nodes know which node is an intended receiver of the current transmitted data packet. Thus, all neighbor nodes wake up and keep listening on the long preamble and finally receive the followed data packet, at least the header part containing destination ID. This unnecessary overhearing of non-intended receivers badly affects on network-wide energy conservation. Even though the aforementioned problems of LPL has been lessened in previously proposed schemes [10, 11], still there are additional overheads or some deficiencies of their own; B-MAC+ [10] can reduce the overhearing of non-intended receivers but does not make the long preamble of sender shorter, and X-MAC [11] can diminish both overhearing and long preamble but incurs a side-effect of using a relatively much longer CCA check time in every wake-up moment.

The following observations motivate us to develop a new LPL approach. First, we notice that the long preamble of sender is inevitable for broadcast transmission because it requires waking all neighbor nodes, whereas it causes non-intended receivers overhear in unicast transmission. Second, broadcast traffic is likely constant such as routing beacon but unicast traffic is relatively dynamic. Third, the traffic load of node is different that depends on some topological position, For example, leaf nodes in collection tree based networks [12] take relatively lower traffic load than non-leaf nodes. Thus, we need to eliminate the overhearing and support truly adaptive LPL.

In this paper, we propose a novel LPL approach called *dual wake-up LPL* (DW-LPL). Our approach supports two different types of transmission mode: *transmitter-initiated mode* (TIM) and *receiver-initiated mode* (RIM); Sensor nodes sleep and wake up according to two independent schedules, channel polling schedule and beacon sending schedule. Channel polling is periodically scheduled for TIM as in the check interval of LPL. In addition, beacon sending time is scheduled for data transmission with RIM, where a beacon is

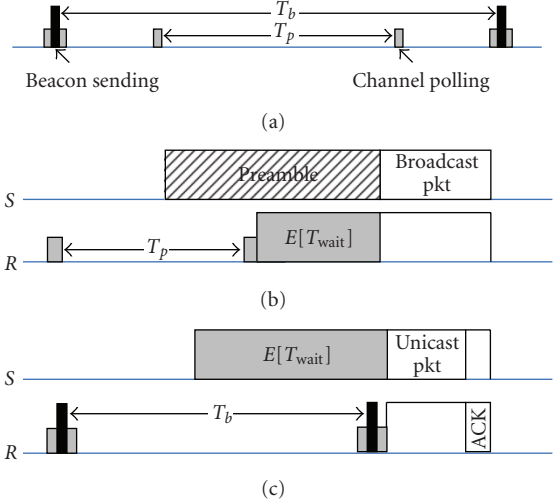


FIGURE 2: Dual wake-up low power listening (DW-LPL): (a) channel polling and beacon sending wake-ups; (b) transmitter-initiated transmission mode; (c) receiver-initiated transmission mode.

a sort of signal representing Ready to Receive [13]. In RIM, sender first waits for a beacon from receiver. If sender receives the beacon successfully, it immediately transmits the pending data packet to the receiver.

Through analysis on energy consumption, we present that our *dual wake-up LPL* (DW-LPL) can provide more efficient energy performance than single wake-up LPL in spite of an extra overhead sending beacon and in particular better adaptability for sporadic traffic. In experiments using real sensor devices, we show that our adaptive DW-LPL schemes (AIMD and AIMD + MW) are effective for energy conservation in practical sensor network topologies and traffic patterns.

The rest of this paper is organized as follows. In Section 2, we introduce the basic concept of our dual wake-up approach. In Section 3, we analyze the energy performance of LPL and our approach via radio energy model, and compare them for sporadic traffic. And then, we propose adaptive DW-LPL schemes using AIMD and AIMD + MW rules in Section 4. In Sections 5 and 6, we describe an implementation perspective and evaluate the experimental results of the proposed adaptive schemes, respectively. In Section 7, we summarize related work and conclude in Section 8.

2. DUAL WAKE-UP APPROACH

Our approach, DW-LPL, provides two wake-up types for two different transmission modes, respectively. One wake-up type is for transmitter-initiated transmission mode (TIM) using preamble sampling technique. The other wake-up type is for receiver-initiated transmission mode (RIM) introduced newly to improve the adaptation ability. We define two independent wake-up schedules as shown in Figure 2(a). According to the channel polling schedule, all nodes wake

up to check the activity of channel every channel polling interval, T_p . Similarly by the beacon sending schedule, they also wake up to broadcast a beacon which is a short packet containing the sending node's ID every beacon sending interval, T_b .

In TIM, sender follows the same behavior as in LPL but some constraints added. TIM is mainly used to transmit broadcast packets as shown in Figure 2(b). Because the nodes in the vicinity of sender wake up in the duration of long preamble equal to T_p , they detect the preamble and wait for the following broadcast packet to be received. By limiting the use of TIM into broadcasting, the overhearing problem of TIM can be avoided in handling unicast traffic. And also T_p can be optimally fixed over network lifetime after setting at initial network configuration through evaluating the amount of average broadcast traffic. The amount of broadcast traffic depends on what kind of data gathering and routing protocols are used. Based on conventional sensor data gathering protocols such as dissemination/collection on tree topology, broadcast traffic ratio is relatively low in total data traffic, for example, 1%, so the amount is small and constant over some time window.

RIM is used only for transmitting unicast packets. In RIM, sender waits for the beacon to be sent from the intended receiver instead of transmitting the packet with long preamble, as shown in Figure 2(c). The waiting duration should be long enough as much as T_b of receiver. After receiving the beacon, sender starts to transmit the pended unicast packet through CSMA contention among other potential senders. The receiver further waits for maximum CSMA backoff time (e.g., 10 ms) after receiving any packet to give a transmission opportunity to contending senders. If there is no incoming packet, the receiver goes back to sleep mode. Otherwise, it receives the actual unicast packet from sender and responds with ACK packet. At the expense of sending beacon at receiver side, RIM eliminates the overhearing of nonintended receivers at transmitting unicast packets. Each node can set its own optimal T_b adaptively according to the incoming rate of unicast packets. Thus, the beacon sending interval of each node can be adjusted independently for adaptive listening.

DW-LPL approach is more flexible than LPL in supporting an adaptive listening. Each node can schedule its T_b by estimating the amount of incoming traffic. For example, node increases its T_b whenever no data packet responds after broadcasting beacon, otherwise T_b can be decreased. Furthermore, the beacon sending schedule of RIM may stop to reduce energy consumption when incoming traffic is idle for a long time. In this case, TIM can be used as a backup transmission mode to resume the beacon sending schedule of receiver. We will describe in detail adaptive listening schemes for DW-LPL in Section 4.

3. ANALYSIS

In this section, we first set up a radio energy model and analyze LPL and our dual wake-up LPL (DW-LPL) in terms of energy consumption. And then, we analytically show the necessity of adaptive LPL for sporadic traffic and how much

TABLE 1: Typical power and measured time values for Telosb 802.15.4 CC2420 radio and CSMA/CA, and symbols used in radio energy analysis.

Symbol	Meaning	CC2420
P_l	Power in listening	56.4 mW
P_t	Power in transmitting	52.2 mW
P_r	Power in receiving	56.4 mW
P_a	Power in awaking	670 uW
P_s	Power in sleeping	3 uW
t_a	Time to awake	1.46 ms
t_{cca}	Average CCA check time	3 ms
t_B	Time to Tx/Rx a byte	32 us
t_g	Guard time after sending beacon	10 ms
t_{ib}	Average initial backoff time	5.12 ms
t_{cb}	Average congestion backoff time	2.56 ms
L_b	Beacon packet length	10 B
L_d	Data packet length	60 B
T_p	Channel polling interval	Varying
T_b	Beacon sending interval	Varying
T_d	Data generation interval	Varying
R_d	Data generation rate ($1/T_d$)	Varying

DW-LPL saves the energy consumption by implementing the flexible traffic adaptation in tree based sensor network topologies.

3.1. Radio energy model

We focus on radio energy consumption in wireless sensor nodes. Having different power consumption levels, a radio device has one of the following states: listen, transmit, receive, awake, and sleep. Thus, the expected energy consumption can be simply modeled by (1) with the fractional time staying in each state per unit time (1 sec). We denote the power consumed in each state as P_l , P_t , P_r , P_a , P_s , and the expected time staying in each state as Δ_l , Δ_t , Δ_r , Δ_a , Δ_s , respectively. For a low power listening approach, we can formulate the Δ items and finally get the energy consumption of (1) with the sleep time $\Delta_s = 1 - \Delta_l - \Delta_t - \Delta_r - \Delta_a$:

$$\xi = P_l\Delta_l + P_t\Delta_t + P_r\Delta_r + P_a\Delta_a + P_s\Delta_s. \quad (1)$$

We use the symbols presented in Table 1 for typical power and time values required in calculating the Δ items. For analysis, we refer some power and time values in the actual sensor device using CC2420 radio. In particular, P_a is the average power of turning radio on in two phases and t_a is the time taken in the two phases—0.6 ms taken with 60 uW for turning voltage regulator on and 0.86 ms taken with 1.095 mW for crystal oscillator—as specified in CC2420 specification [14]. t_{cca} is the measured check time taken in performing the sequence of CCAs to detect a wake-up preamble. For simplicity, we assume that all nodes are in transmission range and each node sends data packets at the rate R_d .

3.1.1. CSMA/CA model

We need to capture the effect of CSMA/CA channel access mechanism in our analysis. For this purpose, we apply an unslotted CSMA/CA model to derive the carrier sensing time, T_{cs} , which can impact on radio energy consumption in CSMA/CA based systems. We use the result of performance analysis on IEEE 802.15.4-based unslotted CSMA/CA in [15]. Based on the result of [15], we formulate the channel busy probability (γ) by simplifying backoff mechanism; we assume a flat backoff mechanism used in TinyOS [16] instead of an exponential backoff mechanism assumed in [15]. In (2), γ is a ratio of channel occupation time of neighbors in one busy period where T_d is the data generation interval, T_{tx} is the time to transmit a packet in radio channel and n is the number of neighbors. T_{tx} can be changed according to the sleep interval of LPL. Thus, γ reflects the effect of LPL transmission. Using γ , we can derive the expected carrier sensing time like (3) where t_{ib} is the average initial backoff time and t_{cb} is the average congestion backoff time. As γ affects the number of congestion backoff trials, T_{cs} increases with γ . In later analysis, by defining each T_{tx} for both LPL and DW-LPL, we calculate T_{cs} reflecting the stochastic behavior of CSMA/CA on energy consumption:

$$\gamma = \frac{nT_{tx}}{T_d - T_{tx}}, \quad (2)$$

$$T_{cs} = t_{ib} + \left(\frac{1}{1 - \gamma} - 1 \right) t_{cb}. \quad (3)$$

3.1.2. LPL energy model

The radio energy model for LPL is specified as (4)–(8). LPL requires a long preamble for packet transmission and its duration is determined by receiver's sleep interval, T_p . Thus, T_{tx} of LPL becomes $T_p + L_d t_B$ and we have T_{cs} derived from T_{tx} in (2) and (3). Δ_l of (5) is the time a node spends in performing carrier sensing at the sending rate, R_d , and the sequence of CCAs to detect the channel activity at the channel polling rate, $1/T_p$. Δ_t of (6) is the time in transmitting the long preamble and data packet itself at the rate R_d . Δ_r of (7) is the time in receiving data packets sent from neighbors at the rate nR_d , where $T_p/2$ is the average waiting time before receiving actual data packet. Lastly, Δ_a of (8) is the time a node spends in awaking from sleep mode at the channel polling rate, $1/T_p$. Note that each channel polling instance takes $(t_a + t_{cca})$ time in awaking from sleep mode and checking out channel, thus t_{cca} and t_a have been separately counted into (5) and (8) due to having different power levels:

$$T_{tx} = T_p + L_d t_B, \quad (4)$$

$$\Delta_l = T_{cs} R_d + \frac{t_{cca}}{T_p}, \quad (5)$$

$$\Delta_t = (T_p + L_d t_B) R_d, \quad (6)$$

$$\Delta_r = n \left(\frac{T_p}{2} + L_d t_B \right) R_d, \quad (7)$$

$$\Delta_a = \frac{t_a}{T_p}. \quad (8)$$

3.1.3. DW-LPL energy model

The radio energy model for DW-LPL specifies the total energy consumption in both TIM and RIM separated by the broadcast traffic ratio, δ . The δ ratio of total data rate, that is, δR_d , is transmitted with TIM and the ratio $(1 - \delta)$ of total data rate, that is, $(1 - \delta) R_d$, is transmitted with RIM. As additional parameters, we define the beacon sending interval, T_b , and the beacon packet length, L_b . In DW-LPL, T_{tx} is defined as (9) by considering beacon transmission for RIM. Equations (10)–(13) specify the Δ items. Δ_l of (10) includes (5) of LPL, one extra carrier sensing time required before sending beacon and a guard time, t_g to receive an incoming packet after sending beacon at the rate, $1/T_b$. The transmission time in Δ_t of (11) is separated into two parts by δ , $(T_p + L_d t_B)$ in TIM and $L_d t_B$ in RIM. In addition, Δ_t includes the time for transmitting beacon at the rate $1/T_b$. Likewise, the reception time in Δ_r of (12) is also separated into two parts by δ , $n(T_p/2 + L_d t_B)$ in TIM and $(T_b/2)$ in RIM, where $T_p/2$ in TIM is the expected waiting time of receiver until actual data packet arrives, that is, $E[T_{wait}]$ in Figure 2(b), and $T_b/2$ in RIM is the expected waiting time of sender until the intended receiver's beacon is received, that is, $E[T_{wait}]$ in Figure 2(c). Lastly, Δ_a of (13) includes one extra awaking time at the beacon sending rate, $1/T_b$, as well as (8) of LPL. Note that each beacon sending instance takes $(t_a + t_{cs} + L_b t_B + t_g)$ time in awaking from sleep mode, sending beacon and waiting for packet, thus $t_{cs} + t_g$, $L_b t_B$ and t_a have been separately counted into (10), (11), and (13) due to having different power levels:

$$T_{tx} = \delta(T_p + L_d t_B) + (\delta - 1)L_d t_B + \left(\frac{T_d}{T_p} \right) L_b t_B, \quad (9)$$

$$\Delta_l = T_{cs} R_d + \frac{t_{cca}}{T_p} + \frac{(T_{cs} + t_g)}{T_b}, \quad (10)$$

$$\Delta_t = (T_p + L_d t_B) \delta R_d + L_d t_B (1 - \delta) R_d + \frac{(L_b t_B)}{T_b}, \quad (11)$$

$$\Delta_r = n \left(\frac{T_p}{2} + L_d t_B \right) \delta R_d + \left(\frac{T_b}{2} \right) (1 - \delta) R_d, \quad (12)$$

$$\Delta_a = t_a \left(\frac{1}{T_p} + \frac{1}{T_b} \right). \quad (13)$$

With the radio energy model, we can find the optimal wake-up intervals, T_p and T_b , to minimize the energy consumption in LPL and DW-LPL by assuming the traffic is periodic. Since the two parameters are independent in (1) of DW-LPL with the Δ items (10)–(13), the optimal channel polling interval, T_p^* , satisfying $d\xi/dT_p = 0$ and the optimal beacon sending interval, T_b^* , satisfying $d\xi/dT_b = 0$ can be calculated for given data rate R_d and broadcast traffic ratio δ . Likewise, the optimal interval of LPL is a result of differentiating (1) instantiated with the Δ items (5)–(8). Figures 3(a) and 3(b) show that there exist optimal intervals for LPL and DW-LPL in terms of energy consumption. As expected, T_p^* of LPL and T_b^* of DW-LPL increase as data rate decreases; T_p^* is constrained with the length of long preamble and channel polling overhead, T_b^* is restricted with the beacon waiting time and beacon sending overhead.

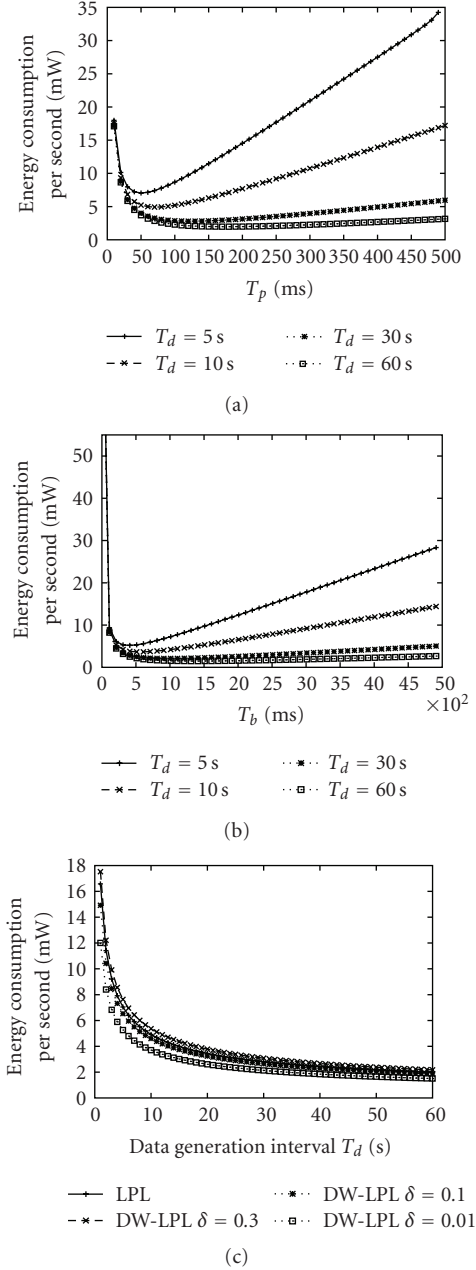


FIGURE 3: The analysis results for LPL and DW-LPL radio energy model: (a) energy consumption for varying T_p in LPL ($n = 10$); (b) energy consumption for varying T_b in DW-LPL ($n = 10, \delta = 0.01, T_p^*$); (c) energy consumption comparison for varying R_d in LPL and DW-LPL.

Figure 3(c) shows the radio energy consumptions for LPL and DW-LPL by applying the optimal intervals. Comparing with LPL, DW-LPL improves the energy performance by RIM but it depends on δ . For a large broadcast traffic ratio, for example, $\delta = 0.3$, DW-LPL consumes more energy than LPL because it costs long preamble transmission in TIM as well as beacon sending in RIM. However, DW-LPL can improve the energy performance even for relatively large broadcast traffic ratio by introducing adaptive beaconing

concept; In following sections we analyze the benefit of traffic adaptation for sporadic traffic and describe adaptive schemes for DW-LPL.

3.2. Low power listening for sporadic traffic

Many sensor applications periodically generate traffic for data collection. At every collection period, each node has different workload which depends on how many descendants are there on routing tree as shown in Figure 4(a). And data packets are collected sporadically at the beginning part of collection period, not evenly distributed over collection period. Thus, we need to reduce energy consumption during inactive traffic period (T_{off}) by introducing adaptive wake-up intervals in LPL and DW-LPL.

To show the benefit of adaptive listening for sporadic traffic, let us introduce an idealized LPL where the wake-up interval, T_p , is completely adapted over time-varying traffic pattern. Figure 4(b) shows the packet arrival patterns on some node for both periodic traffic and sporadic traffic. For simple analysis, the broadcast packets as background traffic are arrived with a fixed rate in both traffic patterns. The unicast packets are arrived periodically over T time frame in periodic traffic pattern, whereas in sporadic traffic pattern all unicast packets arrive in T_{on} period and no unicast packets arrive in T_{off} period. In case of using LPL for sporadic traffic pattern, the energy consumption is the same as for periodic traffic pattern since the check interval, T_p , is not changed over T time frame. In contrast, T_p in the idealized LPL adaptively changes at each T_{on} and T_{off} period according as data rate changes. Let $T = 1$, total data rate r , and broadcast traffic ratio δ , respectively. The energy consumption equation of ideal LPL can be formulated to (14) where $\xi(x)$ means (1) with the data rate x and the optimal interval T_p^* in LPL. In (14), the increased data rate, r/T_{on} , is applied during T_{on} and the decreased data rate, δr , is applied during T_{off} :

$$\xi^* = T_{\text{on}} \xi\left(\frac{r}{T_{\text{on}}}\right) + T_{\text{off}} \xi(\delta r). \quad (14)$$

Figure 5 shows the energy consumptions for sporadic traffic with varying data rate. ξ^* of ideal LPL consumes much lower energy than LPL at $\delta = 0.3$ and $T_{\text{on}} = 0.1$, the difference becomes larger as either δ or T_{on} decreases. Figure 5 also shows the energy consumption of idealized DW-LPL where T_p and T_b are optimally calculated over time. Once our proposed DW-LPL is perfectly tuned to be adaptive, the energy performance is greatly improved even for large broadcast traffic ratio, for example, $\delta = 0.3$. Moreover, DW-LPL is more flexible than LPL in supporting adaptive listening because T_b can be independently changed regardless of other nodes.

4. ADAPTIVE LOW POWER LISTENING SCHEMES

There are limitations in supporting adaptive LPL. In LPL mechanism, sender should know T_p of receiver to determine the proper preamble length. If the preamble length is shorter than T_p , receiver may not detect the preamble of sender.

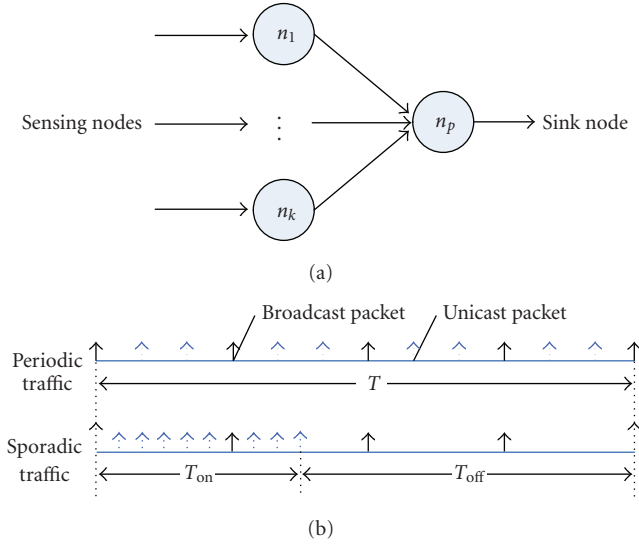


FIGURE 4: The collection tree based topology and traffic patterns: (a) the parent node, n_p can have k children, n_1 – n_k in collection tree; (b) periodic traffic and sporadic traffic.

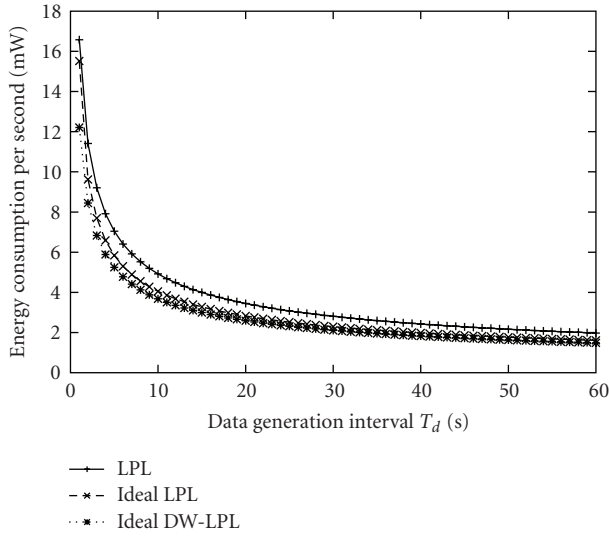


FIGURE 5: The energy consumption comparison for sporadic traffic ($\delta = 0.3$ and $T_{on} = 0.1$).

Conversely the energy is unnecessarily wasted if the preamble length is longer. By this reason, T_p has been used as a fixed configuration parameter over all nodes in LPL. However, to make the adaptive version of LPL possible, we need to change T_p independently in each node and moreover inform the changed value to neighbor nodes. Some piggybacking or signaling method can be used for this purpose of advertising the changed interval but it cannot avoid the overhead of neighbor management and information synchronization among nodes.

In our DW-LPL where two transmission modes, TIM and RIM, are used, adaptive LPL schemes can be easily constructed due to the following reasons. T_p can be fixed

as a prior configuration parameter over all nodes because TIM is designed to be mainly used for broadcast packets and broadcast traffic is likely periodic and predictable. On the other hand, T_b is self-adaptable for the dynamic load of unicast traffic in each node because RIM itself is able to sense the traffic behavior of incoming unicast packets by counting the packet reception after sending beacon. And also, RIM has a safeguard named TIM, in other words, TIM can be used as a backup if RIM fails due to no reception of receiver's beacon. With this backup mechanism, we can make adaptive beaconing more flexible. In receiver side, the unicast packet received with TIM signals receiver that its beacon sending interval should be shorten or its beacon sending itself should be restarted if disabled. Thus, in DW-LPL, each node can adaptively change its own T_b by some predefined wake-up beaconing rules. We propose two adaptive beaconing rules (AIMD and AIMD + MW) in this section.

4.1. Additive increase multiplicative decrease (AIMD)

We define four constant parameters for AIMD beaconing rule: $MaxT_b$, $MinT_b$, α , and β . $MaxT_b$ and $MinT_b$ are maximum and minimum values that calculated by the estimated minimum and maximum unicast data rate. The α and β are well known parameters as increasing and decreasing constants in AIMD algorithms. All nodes initially start its beacon sending with the interval $T_b = MaxT_b/2$. In RIM using AIMD beaconing rule, sender first waits for receiver's beacon before transmitting unicast data packet. If sender does not receive the corresponding beacon during $MaxT_b$ time, the transmission fails. Receiver has increase or decrease T_b in accordance with the following rule after sending its beacon; if no unicast packet is responded for sending beacon, receiver increases its T_b with (15). Otherwise, receiver decreases its T_b with (16):

$$MIN(T_b + T_b\alpha, MaxT_b), \quad \text{where } 0 < \alpha < 1, \quad (15)$$

$$MAX\left(\frac{T_b}{\beta}, MinT_b\right), \quad \text{where } \beta > 1, \quad (16)$$

$$n \geq \frac{\log(MaxT_b/MinT_b)}{\log(\beta)} \iff \frac{MaxT_b}{\beta^n} \leq MinT_b, \quad (17)$$

$$n \geq \frac{\log(MaxT_b/MinT_b)}{\log(1+\alpha)} \iff MinT_b \sum_{i=0}^n \binom{n}{i} \alpha^i \geq MaxT_b. \quad (18)$$

By applying AIMD beaconing rule, nodes can control its beacon sending interval according to its incoming traffic load. In an active traffic period, T_b of the parent receiver converges to $MinT_b$ after n th beacon sending wake-up time since there are incoming data packets, where n is subjected to the condition (17). After the active period ends, this time T_b converges to $MaxT_b$ after n th beacon sending wake-up time due to no incoming data packet, where n is subjected to the condition (18). The convergence rate of both increasing to $MaxT_b$ and decreasing to $MinT_b$ mainly depends on α and β .

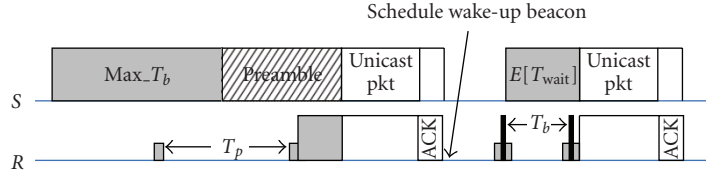


FIGURE 6: The adaptive DW-LPL scheme with AIMD + MW.

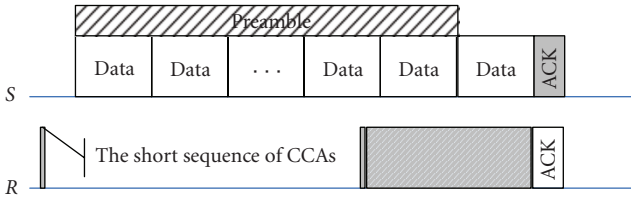


FIGURE 7: Experimental LPL method in TinyOS 2.x [17].

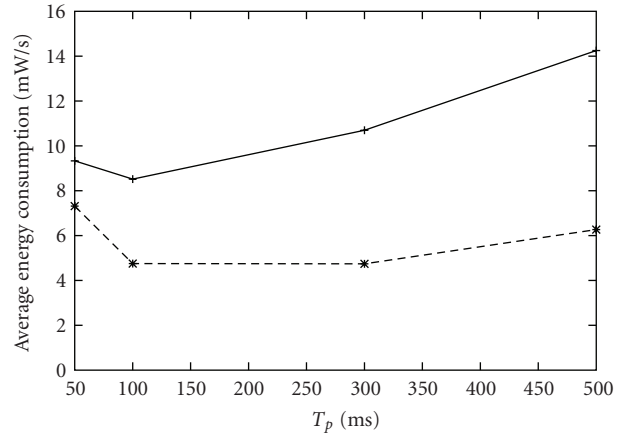
4.2. AIMD with moving worker (AIMD + MW)

We add the concept of moving worker (MW) to AIMD adaptive beaconing rule. Conceptually a moving worker machine operates like starting with some event detected and stopping with no event detected for a time. In the same concept, each node stops sending its beacon when T_b is increased up to $MaxT_b$ since there is no incoming packet for a certain time. TIM is used to signal the start of sporadic traffic, as shown in Figure 6. Having a unicast packet, sender first waits for the beacon from receiver during $MaxT_b$ time. If there is no beacon, it transmits the unicast packet by TIM for receiver to restart sending its wake-up beacon. After receiving the unicast packet transmitted with TIM, the receiver starts sending its beacon with $T_b = MaxT_b/2$. The remaining operations of receiver follow the AIMD beaconing rule such as increasing/decreasing T_b . As a result, since there is no need sending beacon in idle period, the MW rule improves the energy performance in sensor networks having a long idle period.

5. IMPLEMENTATION

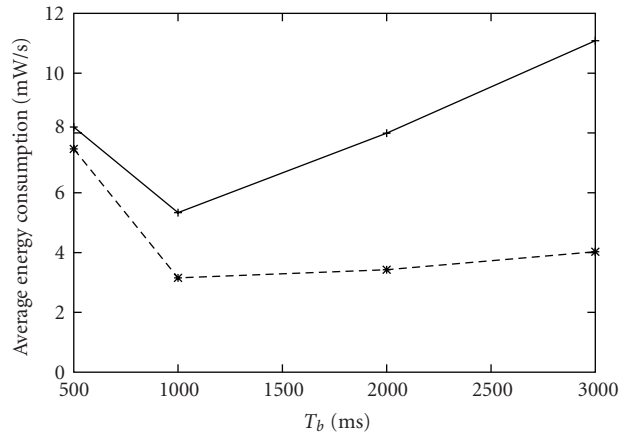
We implemented our dual wake-up LPL functionality in the CC2420 radio stack [17] of TinyOS 2.x [16]. Unlike the unstructured layering of TinyOS 1.x, TinyOS 2.x provides the enhanced radio stack with well structured layers. In TinyOS 2.x, LPL layer is led to be located on top of CSMA Mac layer. Thus, the dual wake-up LPL (DW-LPL) can be placed on the radio stack as a stackable module.

In implementation perspective, the long preamble used in LPL cannot be directly implemented in CC2420 radio [14] supporting IEEE 802.15.4 standard [18] because it limits the size of preamble. By this reason, one LPL method emulating the long preamble has been experimentally implemented in TinyOS 2.x [16]. As in Figure 7, this method supports similar functionality with LPL by sending the chunk of data packets acting as a long preamble. In our implementation, the TIM of DW-LPL is designed to transmit a packet in the same way.



—+— LPL ($T_d = 10$ s)
 -*- LPL ($T_d = 30$ s)

(a)



—+— DW-LPL ($T_d = 10$ s)
 -*- DW-LPL ($T_d = 30$ s)

(b)

FIGURE 8: The experiment result for varying wake-up intervals ($n = 10$): (a) LPL; (b) DW-LPL.

For outgoing packets, DW-LPL module first decides which transmission mode will be used according to the destination ID. If the ID is broadcast address, the packet is tried in TIM context. Otherwise, the packet is tried in RIM context. As described in Section 4, for adaptive listening, if the transmission in RIM context fails then the context transition from RIM to TIM is followed with the unicast packet with a special indicator.

We implemented an instrumentation code in CC2420 CSMA layer of TinyOS 2.x to measure the energy consumption. CSMA layer provides the functionality of powering radio on/off so we can hook the start/end instants of each power state. The instrumentation measures the Δ time for each radio power state using 32 kHz Timer. We calculate the energy consumption of (1) by using measured Δ times.

6. PERFORMANCE EVALUATION

We evaluate the performance of DW-LPL via real experiment using sensor motes (Telosb) with CC2420 radio supporting IEEE 802.15.4 standard. Our metrics are energy consumption and packet latency. We consider three experimental setups. In basic setup, we locate several motes acting as sender around one node serving as receiver and traffic is generated periodically from all senders at the same rate. At tree setup, the basic topology is emulating one instance of parent-children relationship at the collection tree topology as shown in Figure 4(a), and the sporadic traffic is generated by node-specific different rates. To show the latency characteristic of DW-LPL as well as energy consumption, in multihop setup, we construct a chain topology to deliver packets to one sink node. In all experiments, we use 0 dBm transmission power and achieve reliable packet delivery via link-level retransmission. Below experimental results are average values of repeating the same experiment 3 times or more, where each experiment lasts at least 10 min.

6.1. Basics

We first show the energy consumption of LPL and DW-LPL for varying the wake-up intervals, and compare the energy consumption of DW-LPL against LPL. In this experiment, we use one receiver and 10 sending nodes in basic setup, and each sender generates unicast traffic at every data generation interval, T_d ; Since there is no broadcast traffic, we disable the channel polling of DW-LPL. Figure 8 shows the average energy consumption per node of LPL and DW-LPL for varying sleep intervals, T_p for LPL and T_b for DW-LPL. In Figure 8(a), $T_p = 100$ ms is best for data generation interval $T_d = 10$ s. For $T_d = 30$ s, the optimal T_p lies between 100 ms and 300 ms. In case of DW-LPL, as shown in Figure 8(b), the optimal T_b can be found in between 1 s and 2 s for the same data rates. Those results follow our analysis result in Section 3. According to this basic experiment, we use $T_p = 100$ ms and $T_b = 1$ s for similar workload in the following experiments, and if not explicitly specified, the following AIMD parameters are used: $\text{Min}T_b = 500$ ms, $\text{Max}T_b = 5$ s, $\alpha = 0.1$ and $\beta = 2$.

6.2. Overhearing exemption effect

We investigate on the overhearing exemption effect of DW-LPL for unicast traffic (i.e., $\delta = 0$) in basic setup. In this case, we compare energy consumption at varying the number of transmission nodes (n) from 2 to 8 nodes. Figure 9 shows the result of LPL and DW-LPL (AIMD + MD enabled) at $T_d = 10$ s. The energy consumption of

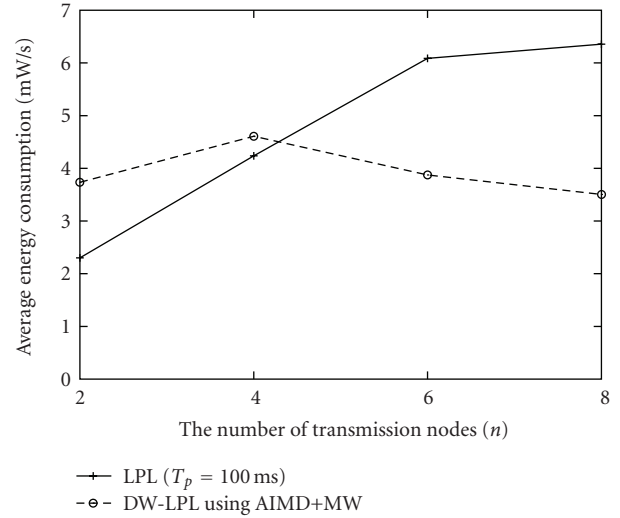


FIGURE 9: The experiment result of LPL and DW-LPL for varying the number of transmitters.

LPL ($T_p = 100$ ms) increases linearly with n due to the overhearing problem, whereas the energy consumption of DW-LPL remains almost horizontally regardless of n . With AIMD + MW beaconing rule, the beacon sending interval of receiver changes adaptively according to the aggregated data rate of n senders. MW rule is rarely fired when $n \geq 4$ since T_b does not exceed $\text{Max}T_b = 5$ sec. When the incoming packet rate is low, that is, $n = 2$, the beacon interval increases to relatively longer length. Thus, MW rule can be fired at times. Together with reduced overhearing, that is why LPL is better than DW-LPL at $n = 2$ in Figure 9. In particular, we can see that the energy consumption of DW-LPL is getting lower when n increases over 6. This is due to AIMD rule at receiver side, which makes T_b shorter for increased data rate. In a result, the expected beacon waiting time in all senders decreases.

6.3. Adaptive beaconing effect

In tree experiment, we consider one parent node and six child nodes. Three sets of two child nodes generate the data packets at different rate, that is, $T_d = 1$ sec, 5 sec, and 10 sec, respectively. And the traffic pattern of those sets is sporadic like repeating 30 sec active period and 150 sec idle period as shown in Figure 4(b). All senders generate broadcast packets at 30 sec interval in both active and idle period, thus the aggregated broadcast traffic ratio is roughly $\delta = 0.31$ from the unicast versus broadcast ratio, that is, $78(= 30 \times 2 + 6 \times 2 + 3 \times 2) : 36(= 6 \times 6)$ in 180 sec time frame. The experiment lasts during 30 min. Figure 10 shows the normalized energy consumption per node. At $T_p = 300$ ms, DW-LPL with AIMD + MW rule shows 25% better performance than LPL, and when $T_p = 500$ ms, we saves 35% energy. Those improvements come from the effect of adaptive listening of DW-LPL using AIMD+MW beaconing rule. During the long idle period, the receiver's beacon sending is slowly down and finally stopped at $T_b = \text{Max}T_b$ by MW rule. To measure this

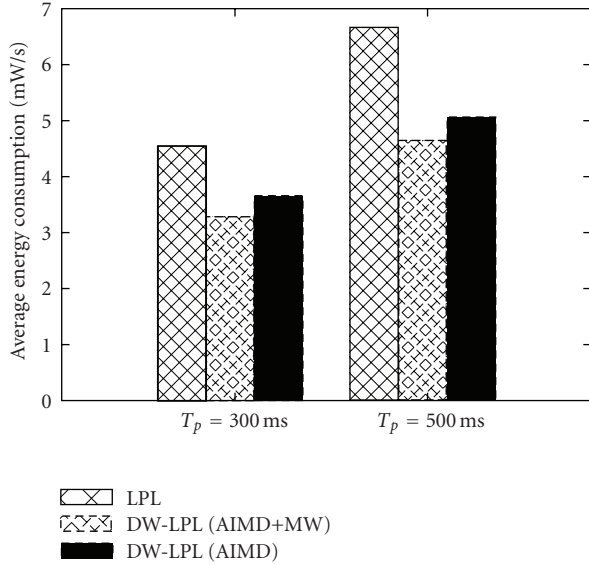


FIGURE 10: The experiment result on energy consumption in tree setup.

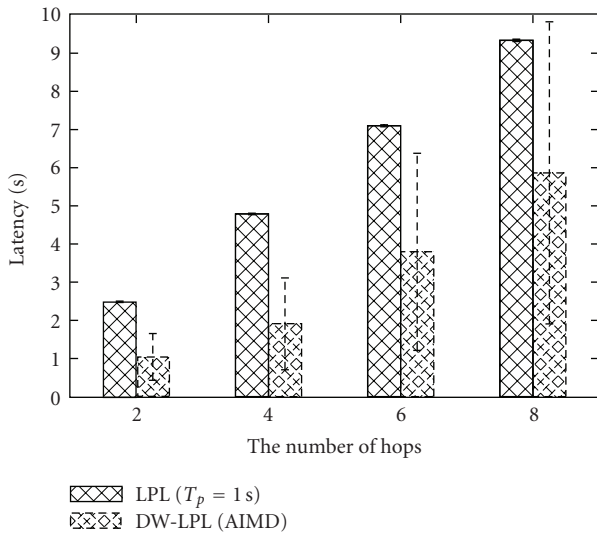


FIGURE 11: The experiment result on packet latency in multihop setup.

MW effect, we additionally show the energy performance of the DW-LPL using only AIMD rule in the figure, where using MW rule in this experiment saves about 10% energy.

6.4. Packet latency

In multihop setup, we use a chain topology consisting of one sink node, multiple intermediate nodes. All nodes except for sink node generate a packet so that the traffic load increases as closer to sink node. As a result, the average beacon sending interval, T_b , of each intermediate node is maintained with smaller value according to its traffic load. Each node generates one packet per 10 s and the latency is

measured for packets arriving at sink node. Figure 11 shows the packet latency for LPL and DW-LPL in chain topology. Each box indicates the mean and standard deviation of 100 packet latency samples. By given check interval $T_p = 1$ s, the packet latency of LPL is proportional to the number of hops having almost fixed forwarding delay per hop. DW-LPL is much better than LPL averagely. However, DW-LPL shows big variance as the number of hops increases. This is directly from following AIMD beaconing rule; in long multihop path, the faraway nodes from sink may have relatively long beacon sending interval at times due to rare incoming traffic. The variance of packet latency is strongly affected by $MaxT_b$ in DW-LPL. As a consequence, DW-LPL sacrifices some jitter of packet latency in long multihop environment for improving the performance of energy conservation.

7. RELATED WORK

Dutycycling technique has been studied to improve energy efficiency in wireless sensor networks. There are broad research areas including dutycycling MAC (MAC level), dutycycling using topology control (routing level), application-specific dutycycling (application level), and so forth. We first look over those areas and then focus on dutycycling MAC as closely relevant work.

Application-specific dutycycling controls the sleep schedule of nodes by using application-specific information such as when data transfer starts and ends; Nodes sleep as much as possible according to application activity. This *application-informed approach* has also been explored in various contexts. Koala [19] coordinates its sleep schedules for bulk transfer application. There are proposals to let the applications configure the power management policies based on their communication requirement [20, 21].

Dutycycling at Routing level can be achieved by topology control and energy-aware routing. First, *topology control* attempts to save energy by turning off nodes that are not affecting on routing fidelity or sensing fidelity. SPAN [22], ASCENT [23], and GAF [24] are typical examples for this approach. Second, *energy-aware routing* improves network lifetime by evenly spreading the forwarding burden over nodes where routing decision considers node’s residual energy. Examples of this work includes [25–27].

Dutycycling MAC improves energy efficiency by reducing idle listening at MAC level. There are two major approaches, *synchronized listening* and *low power listening*. Synchronized listening coordinates nodes to sleep and wake-up according to globally synchronized schedule. S-MAC [6], T-MAC [7], and SCP-MAC [8] are typical MAC examples based on synchronized listening. Low power listening (LPL) approach does not explicitly coordinate the sleep schedule across nodes, instead, nodes independently schedules its sleep time; sender transmits a packet after making a rendezvous with receiver. Our DW-LPL is extending this LPL approach by introducing receiver-initiated rendezvous as well as transmitter-initiated rendezvous.

We summarize several previously proposed LPL schemes [10, 11, 28] in conjunction with DW-LPL. WiseMAC [28] proposed an idea exploiting the knowledge of receiver’s

wake-up schedule Knowing the wake-up schedule of direct neighbors, sender can adjust its preamble sending start time to the wake-up time of intended receiver. As a result, sender can use a wake-up preamble of minimized size that brings the energy saving on receivers as well as sender. However, it is hard to get letting sender exactly know the next wake-up time of receiver because the wake-up schedule can be dynamically changed by sending or receiving a packet. This semi-synchronization concept can be applied to DW-LPL without worrying the change of wake-up schedule of neighbors because RIM transmission explicitly is triggered with receiving beacon.

In B-MAC+ [10], the short packet called countdown packet contains receiver's ID and the counter signaling how many countdown packets will be more sent before actual data packet is transmitted. There is no time gap in sending countdown packets sequentially. The receiver heard of one countdown packet at its wake-up period can understand when the actual data packet will be transmitted and who the intended receiver is. Therefore, the receiver can determine its next action whether or not it goes back to sleep mode. B-MAC+ solves the overhearing problem of LPL but it does not reduce the energy consumption of sender since the sequence of countdown packets corresponding to long preamble should be sent. In the other hand, the sender in our DW-LPL is expected to wait up to the half of beacon sending interval of receiver. Also, combining B-MAC+ approach such as the countdown preamble in TIM broadcast transmission can give an opportunity for a receiver to sleep till the actual data packet comes during broadcast transmission.

X-MAC [11] proposes to use the sequence of short control packets instead of long preamble. In X-MAC, sender waits an early ACK packet from receiver after sending a control packet, which is called short preamble in [11], containing receiver ID. The receiver heard of short preamble at its wake-up time promptly responds with ACK packet if the packet is destined to itself. The sender receiving ACK packet is able to send the actual data packet immediately so the transmission can be terminated more early than in case of using long preamble. X-MAC can not only reduce the transmission energy of sender but also solves the overhearing problem by introducing early ACK mechanism. However, as a disadvantage, X-MAC requires relatively longer CCA check time than in LPL since the CCA check time at every wake-up moment must be at least longer than ACK waiting period of sender to safely detect the on-going transmission of short preambles. And also, in CSMA/CA based MAC, default carrier sensing at data transmission should be at least longer than ACK period to prevent other nodes from inadvertently intervening into on-going data transmission. Unlike X-MAC, DW-LPL preserves the short CCA time so there is no extra energy consumption at wake-up time. In addition, DW-LPL approach provides more flexible traffic adaptation through independent beacon scheduling.

8. CONCLUSION

In this paper, we proposed a novel dual wake-up LPL approach for adaptive listening. Through analysis we showed

that DW-LPL supporting two rendezvous mechanisms such as TIM and RIM is at least comparable with LPL in terms of energy consumption, and can support adaptive listening by adding traffic-aware beacon sending schedule to the duty cycled LPL providing basically fixed channel polling schedule for preamble detection. Then, we proposed adaptive DW-LPL schemes using beaconing rules such as AIMD, AIMD + MW. And we implemented those schemes on real mote devices (Telosb) using CC2420 radio and evaluated the performance in real experimentation. As future work, we will design and implement the synchronous DW-LPL where the beacon waiting time of sender in RIM could be optimized by utilizing the next beacon sending time of receiver.

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