Hierarchical Duty-cycling of Wireless Sensors

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***Abstract*—Energy efficiency is critical in many IoT applications with sensors that deliver data over wireless communications. Duty-cycling has been a major method for reducing energy consumption. One popular duty-cycling is MAC duty-cycling where an MCU commands the periodic or adaptive turning on and off of an RF chip. Recently, there has been an increase in the number of RF chips for IoT that are equipped with PHY duty-cycling, a new capability of autonomously switching on and off an RF chip without the use of an MCU. These two schemes working at different layers have different pros and cons in terms of operating time scale, the amount of energy saved when the RF chip is switched off, all of which depend on the characteristics of the MCU and the RF chip. In this paper, we propose a novel protocol named HD-MAC (Hierarchical Duty-cycling MAC) that hierarchically integrates duty-cycling in the MAC and physical layers. By smartly applying the new function of chip-level duty-cycling, HD-MAC is able to further reduce the amount of on-time in MAC duty-cycling; hence, energy efficiency can be improved. To optimize HD-MAC's energy efficiency while achieving a given delay requirement, we formulate an optimization problem and solve it to obtain the optimal parameters in the cross-layer context. We implement HD-MAC on Contiki OS and perform extensive experiments using a real sensor mote Firefly with a CC1200 RF chip. We demonstrate that the energy efficiency of HD-MAC is up to 72% higher than that of existing protocols while still satisfying the delay requirement and sustaining similar reliability.**

***Index Terms*—Wireless Sensor Networks, Internet of Things, MAC, Cross-layer, Duty-cycling**

I. Introduction

As the IoT (Internet of Things) era comes, a variety of IoT applications are emerging. This includes environmental monitoring, surveillance system, smart grid, and home automation. One of the most widely deployed networks for IoT is the Wireless Sensor Network (WSN) where many low power sensors are connected through wireless communication. In WSNs, energy efficiency is one of the most important performance metrics since those sensors are normally battery-powered and often deployed in harsh environments (e.g., volcanoes, war zones, forests) where recharging or replacing the batteries of those sensors is often challenging.

To reduce the energy consumption of RF chips that accounts for at most 50% of the total energy consumption, one can use the idea of switching an RF chip's state between on and off, so as to minimize energy waste caused by idle listening. For example, a sensor's RF chip is turned on only when it is waiting for a packet, otherwise it is turned off most of the time. This process of switching the states of the RF chip is performed by the MCU's on/off command in the MAC layer and is called *MAC duty-cycling* (see Fig. 1(a)). The RF chips in the infancy of WSNs pursued simplicity in the design and also had a limited number of power modes. Thus most of the energy efficient MAC protocols are based just on such MAC-level duty-cycling, e.g, [1]–[14]. Recently, a new function for duty-cycling is incorporated in many RF chips in the market, e.g., CC1101 [15], CC1120 [16], and CC1200 [17] from Texas Instrument, and AX5043 [18] and AX5243 [19] from ON Semiconductor. As shown in Fig. 1(b), in this duty-cycling, one can switch the RF chip's state between on and off autonomously, *without* involving MCU. We call this *PHY duty-cycling*, where PHY denotes the physical layer.

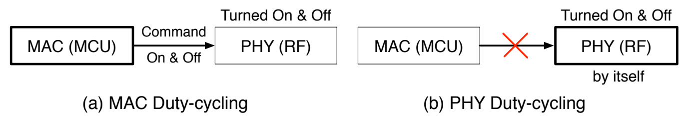


Fig. 1: (a) MAC duty-cycling is performed by MCU commands; hence the time between RF's on and off is limited by MCU's speed. (b) PHY duty-cycling operates without involving an MCU. Thus, the RF is turned on and off rapidly compared to MAC duty-cycling.

As in many engineering ideas, there are different pros and cons in each of the MAC and PHY duty-cycling methods. In MAC duty-cycling, the duty-cycling operation is commanded by an MCU. Thus, the duration that the RF chip stays off is allowed to be significantly long, which makes it appropriate for applications with small traffic volume. However, whenever the RF chip is turned on, it should stay on for a certain amount of time. This is because the operation speed of MAC duty-cycling is limited by the MCU's clock speed and requires communication between the MCU and the RF chip. However, in PHY duty-cycling, the speed of turning on and off the RF chip is high. Thus, when duty-cycling a radio, RF chip only needs to be turned on for a very short amount of time compared to MAC duty-cycling. The weakness of PHY duty-cycling is that the duration that the RF chip is off is shorter than that of MAC duty-cycling since it works with the RF chip's internal clock. Thus, it is impossible to turn off the RF chip for a long duration. These different features of both duty-cycling schemes in terms of sleep time-scale and chip-dependent parameters motivate us to consider a hybrid form of duty-cycling mechanism that aims to have the strengths of both schemes.

In this paper, we propose a novel, hierarchical duty-cycling protocol, called **HD-MAC** (Hierarchical Duty-cycling MAC), which exploits two different sleep time scales of MAC duty-cycling and PHY duty-cycling. By hierarchical, we mean that inside the larger time scale of MAC duty-cycling, we repeatedly apply PHY duty-cycling so as to maximize the RF chip's turned-off time while still achieving given delay requirement. Note that the best combination of merging MAC duty-cycling and PHY duty-cycling significantly depends on different RF device characteristics; thus, it requires to smartly and optimally choose the parameters of our protocol. To tackle this challenge, we formulate a cross-layer optimization problem of maximizing energy efficiency while still achieving a given delay requirement. By understanding the solution structure of the optimization problem and computing its solution numerically, we obtain the optimal choice of the protocol parameters which can be used in operating **HD-MAC**. To evaluate the performance of **HD-MAC**, we use commercial sensor boards, Firefly [20] with CC1200 [17] which supports PHY duty-cycling. We perform extensive experiments to compare with existing works which rely only on either MAC or PHY duty-cycling. We show that our protocol is up to 72% more energy efficient than those protocols while still achieving delay requirements with similar reliability performance.

A. Related Work

For energy-efficient WSNs, a large number of MAC protocols have been studied [1]–[14]. We refer the readers to [21] for a nice survey. The MAC protocols in WSNs can be largely classified as synchronous or asynchronous depending on how to make both a transmitter (TX) and a receiver (RX) turn on their RF chips at the same time.

Synchronous protocols (e.g., [1], [2], [8]) perform clock synchronization periodically by exchanging time-stamped packets. Thus, a TX-RX pair is able to turn on its RF chip almost exactly at the same time, but at a high cost because of synchronization. One approach to reduce such synchronization cost is to use partially synchronous protocols (e.g., [11], [12], [14]), which perform synchronization infrequently but compensate a small amount of clock difference for communication. A different direction from these synchronous schemes is asynchronous ones (e.g., [3], [6], [9]), where by removing synchronization, TX transmits a long MAC preamble to notify its intention of transmission to RX. By receiving a MAC preamble, TX and RX are confirmed to be awake at the same time.

In addition to a lot of protocols based on MAC-layer duty cycling that are listed above, many RF chips supporting the new function of PHY duty-cycling have been released in the market (e.g., [15]–[19]), where the RF chips include the PHY duty-cycling functions such as Wake-on-radio [15], RX Sniff mode [16], [17], and Wakeup-on-Radio [18], [19]. Those functions of the RF chips are able to turn on and off their RF chips while their MCUs remain powered down. Thus, the RF chips can further reduce energy consumption when they are waiting to receive packets.

To the best of our knowledge, there have been no protocols which combine MAC and PHY duty-cycling. In this paper, we propose a hierarchical duty-cycling protocol by synergistically merging both duty-cycling schemes to further optimize energy efficiency. We use X-MAC [6] for MAC duty-cycling and RX Sniff of CC1200 [17] for PHY duty-cycling as an example. There might be slight differences in this merging process depending on which MAC and PHY duty-cycling mechanisms are employed, but we believe that the key idea in taking the strengths from those two can be applied to other combinations.

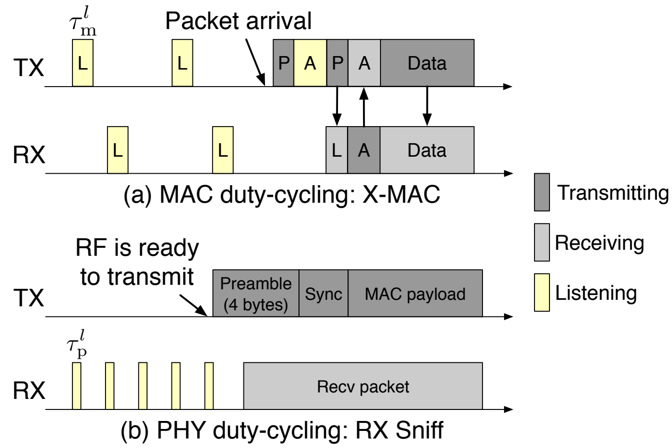


Fig. 2: (a) shows how MAC duty-cycling (X-MAC) works with respect to MAC periodic listening, MAC preamble and ACK. (b) describes PHY duty-cycling using RX Sniff of CC1200. Note that the time scales between (a) and (b) are largely different.

II. HD-MAC Design

In this section, we present HD-MAC (Hierarchical Duty-cycling MAC). We first describe the background of MAC and PHY duty-cycling methods and how to integrate those methods hierarchically, and then we propose additional designs to improve the performances of HD-MAC.

A. MAC and PHY Duty-cycling

MAC Duty-cycling. As a baseline MAC protocol, we choose the asynchronous MAC protocol X-MAC [6]. In X-MAC, before a packet arrives, both TX and RX perform MAC periodic listening, denoted by 'L' in Fig. 2(a), where they turn on their RF chips periodically for a MAC listening time (i.e., $\tau_{\rm m}^l$). When the packet arrives at TX, TX starts to alternately transmit a MAC preamble packet and wait for an ACK from RX, denoted by 'P' and 'A,' respectively. Once RX receives one of the MAC preamble packets during MAC periodic listening, RX transmits an ACK to cut off the MAC preamble. When TX receives the ACK from RX, TX stops transmitting the MAC preamble and starts to transmit the data packet.

PHY Duty-cycling. As an implementation of PHY duty-cycling, we choose RX Sniff in CC1200 [17]. In MAC duty-cycling, the RF chip should be turned on for the specified listening time, which is often long, since it operates by MCU's commands. However, with PHY duty-cycling in CC1200, the RF chip can be turned on only for a very short time (i.e., $\tau_{\rm p}^l$) by repeating the RF chip's state change by itself, while waiting for

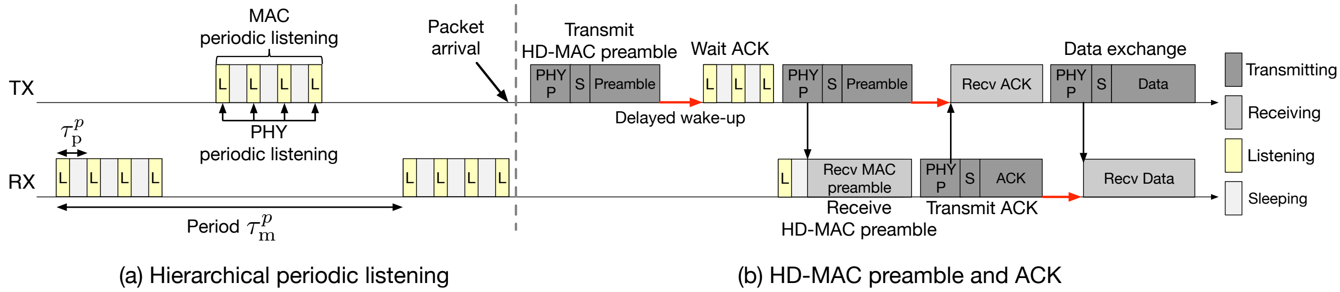


Fig. 3: (a) shows how periodic listening works for both TX and RX before arriving a packet. MAC periodic listening is repeated with the period τ_{m}^{p}. For each MAC periodic listening block, PHY periodic listening is applied such that Listening and Sleeping states are repeated in a short period τ_{p}^{p}. (b) describes the procedure when a packet is generated at TX. TX transmits a HD-MAC preamble packet and waits for an ACK. When RX receives the HD-MAC preamble packet during hierarchical periodic listening, it reacts using the ACK. Once the preamble packet and the ACK are exchanged, TX and RX are ready for data exchange. Red arrows denote delayed wake-up to minimize energy consumption.

a packet. Fig. 2(b) shows the mechanism as yellow rectangles, we call PHY periodic listening. The period of PHY periodic listening is determined by the length of the PHY preamble. For example, the period should be shorter than 0.64 ms so as to detect the PHY preamble, when RF's data rate is 50 kbps and the length of the PHY preamble is 4 bytes. The length of the PHY preamble (e.g., 4 bytes in Fig. 2(b)) is a tunable parameter configured by hardware setting.[1]

B. Basic Operation of HD-MAC

We present how HD-MAC works. Fig. 3 illustrates the overall procedure of HD-MAC, which is composed of hierarchical periodic listening, HD-MAC preamble, and ACK for HD-MAC preamble. In Section II-C, we describe our additional proposal for further optimization: broadcast optimization, heavy traffic optimization, and parameter optimization, which are to further improve the performances of HD-MAC.

(a) Hierarchical periodic listening. When there is no packet to transmit or receive, TX or RX keeps performing hierarchical periodic listening (Fig. 3(a)). In hierarchical periodic listening, MAC periodic listening is performed with the period τ_{m}^{p} in the upper layer. When the RF chip is required to be turned on for the MAC listening time τ_{m}^{l} (denoted by MAC periodic listening in Fig. 3(a)), PHY periodic listening is applied with the period τ_{p}^{p}, so that the RF chip is switched on and off (i.e., switching states over Listening and Sleeping in Fig. 3(a), respectively) by itself to further reduce the energy consumption during τ_{m}^{l}. During PHY periodic listening, the RF chip should be turned on for τ_{p}^{l}, which is the minimum required time to detect the PHY preamble.

(b) HD-MAC preamble and ACK. We take an idea from the MAC preamble of X-MAC [6]. As shown in Fig. 3(b), when a packet arrives, TX starts to transmit HD-MAC preamble. The mechanism of HD-MAC preamble is an iteration of transmitting an HD-MAC preamble packet and waiting for an ACK, where the HD-MAC preamble packet includes the target RX's ID. If TX receives the ACK from its intended RX, it stops transmitting HD-MAC preamble and is ready to transmit a data packet. In terms of RX, while it performs hierarchical periodic listening, the RF chip of RX tries to detect the PHY preamble. Once the PHY preamble is detected, RX keeps turning on the RF chip and tries to decode the signal so as to determine whether the signal is the HD-MAC preamble packet and whether it is intended to itself or not. If RX receives the HD-MAC preamble packet which includes the ID of itself, it transmits an ACK to reply and to stop TX from transmitting HD-MAC preamble. As a result, RX can expect to receive the data packet from TX after transmitting the ACK.

(c) Uniqueness of HD-MAC. We present the HD-MAC's key differences from previous MAC protocols (e.g., X-MAC). Since the period of PHY duty-cycling (i.e., τ_{p}^{p}) is related with the length of the PHY preamble (denoted by PHY P in Fig. 3(b)), we can optimize the energy efficiency of HD-MAC (see Section. III) by controlling the period and the length. Secondly, we apply PHY duty-cycling for every operation of waiting for an ACK. Thus, we can save a lot of energy during waiting for an ACK of HD-MAC preamble. Lastly, the delayed wake-up exploits the unique characteristics of RX Sniff. RX Sniff enables RX to receive a packet with receiving only 4 bits of the PHY preamble. Thus, if TX or RX can expect when a packet is sent (e.g., waiting for an ACK, waiting for data packets), it delays its RF turn on time (represented by red arrows in Fig. 3(b)), so that its RF chip receives the packet with only 4 bits of the PHY preamble. For example, if the PHY preamble is set to 30 bytes, it can save energy by turning off while more than 29 bytes of the PHY preamble is being transmitted.

C. Broadcasting and Adaptive Traffic-dependent Mode

Optimization for broadcast traffic. We optimize broadcast transmissions, i.e., delivering a packet to multiple RXs concurrently. Our optimization for broadcast traffic is explained with respect to the differences from unicast.

- As shown in Fig. 4, while TX transmits HD-MAC preamble for τ_{m}^{p} without termination, it turns off its RF chip while

[1]CC1200 supports the range of the PHY preamble from 0.5 bytes to 30 bytes.

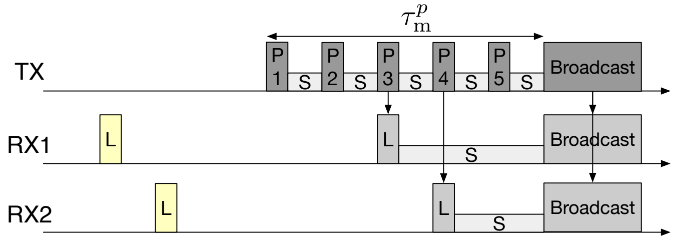


Fig. 4: The optimized operation of the broadcast transmission and reception in HD-MAC.

TABLE I: Symbols in HD-MAC

Symbol	Meaning
τ_{m}^{p}	Period of hierarchical periodic listening
τ_{m}^{l}	RF on time of MAC periodic listening
$\tau_{\text{m}}^{\text{wait}}$	Waiting time for ACK
$\tau_{\text{m}}^{\text{pre}}$	Transmitting time for HD-MAC preamble packet
$\tau_{\text{m}}^{\text{ACK}}$	Transmitting time for ACK
$\tau_{\text{m}}^{\text{data}}$	Transmitting time for data packet
τ_{p}^{p}	Period of PHY duty-cycling
τ_{p}^{l}	RF on time of PHY periodic listening
$\tau_{\text{p}}^{\text{pre}}$	Transmitting time for PHY preamble

waiting for an ACK, denoted by S, if it is for broadcast. Since RXs do not reply to HD-MAC preamble for broadcast with an ACK, TX can turn off the RF chip to reduce energy consumption.

- In terms of RXs, we let RXs turn off their RF chips until the end of HD-MAC preamble, after they receive the HD-MAC preamble packet for broadcast. To know the end of HD-MAC preamble, TX embeds sequence numbers to HD-MAC preamble packets (see Fig. 4, where the sequence numbers are denoted by P1, P2, . . . , P5, respectively). Using the sequence number and τ_{m}^{p}, every RX knows the end of HD-MAC preamble, so that it turns off the RF chip until the end of HD-MAC preamble and then turns on the chip to receive the broadcast packet.

Traffic-driven mode support. Under heavy traffic applications (e.g., data packets are generated in every second), it is well known that MAC duty-cycling protocols (especially asynchronous ones) are not energy efficient. This is because the data packets that arrive very frequently at TX cause a waste of energy due to the MAC preamble. To overcome this limitation, we propose a new mode **HD-MAC-OP** (HD-MAC with Only PHY) which disables MAC duty-cycling and performs PHY duty-cycling only, so that TX can transmit the packet directly without HD-MAC preamble. We note that PHY duty-cycling can be applied to the heavy traffic, since its period of duty-cycling can be much shorter than that of MAC duty-cycling. As a result, HD-MAC works energy efficiently in a wide range of applications from light to heavy traffics. In Section III-C, we describe our proposal on the condition of mode change to HD-MAC-OP.

III. Choice of Optimal Parameters

In this section, we present the optimal choice of parameters based on energy and delay analysis of HD-MAC, formulated by an optimization problem which maximizes the energy efficiency while meeting the delay requirement.

A. Major Parameters

We first present major parameters of HD-MAC and a guideline for parameter optimization. Symbols of HD-MAC in both MAC and PHY are listed in Table I. Detailed analysis of HD-MAC is presented in the following subsection.

- *MAC parameter:* The main parameter in MAC is τ_{m}^{p}, which is the period of hierarchical periodic listening and the maximum length of HD-MAC preamble. The time for waiting an ACK, denoted by $\tau_{\text{m}}^{\text{wait}}$, should be large enough to receive an ACK from RX. To maximize the energy efficiency of HD-MAC, the turned on time of the RF chip, i.e., τ_{m}^{l}, should be minimized during hierarchical periodic listening, but it must ensure that RX is able to receive at least one of HD-MAC preamble packets from TX. The time for transmitting the packet of the MAC preamble, the ACK packet, and the data packet are denoted by $\tau_{\text{m}}^{\text{pre}}$, $\tau_{\text{m}}^{\text{ACK}}$, and $\tau_{\text{m}}^{\text{data}}$, respectively. Since the PHY preamble is appended to each type of packets, they depend on the PHY parameter.
- *PHY parameter:* In terms of PHY, τ_{p}^{p} is the main parameter that denotes the period of PHY duty-cycling. As mentioned earlier, the RF on time of PHY periodic listening (τ_{p}^{l}) is the minimum required time to detect the PHY preamble. To receive a packet from TX while RX performs PHY duty-cycling, the length of the PHY preamble ($\tau_{\text{p}}^{\text{pre}}$) should be longer than the period τ_{p}^{p}, where $\tau_{\text{p}}^{\text{pre}}$ is obtained by the length of the PHY preamble divided by the data rate of the RF chip.

B. Optimal Parameters of HD-MAC

Let E_{TX} and E_{RX} be the energy consumption of TX and RX, respectively. Power consumption of the RF chip with states in transmitting, receiving, and sleeping are denoted by P_{Tx}, P_{Rx}, and P_{sleep}, respectively. Since the power consumption of the RF chip for active receiving and listening do not differ significantly, we use P_{Rx} for both receiving and listening states for simplicity.[2]

We assume that an arrival process of data packets follows a Poisson distribution with rate λ. As shown in Fig. 3, the energy consumption of TX consists of transmitting HD-MAC preamble, which is an iteration of transmitting a HD-MAC preamble packet and waiting for an ACK, and transmitting a data packet. In terms of RX, it consumes energy for performing hierarchical periodic listening, receiving the HD-MAC preamble packet, transmitting the ACK, and receiving the data packet. Then E_{TX} and E_{RX} can be obtained as follows.

$$E_{\text{TX}} = \Big(\tau_{\text{m}}^{\text{pre}} P_{\text{Tx}} + \frac{\tau_{\text{m}}^{\text{wait}}}{\tau_{\text{p}}^{p}} (\tau_{\text{p}}^{l} P_{\text{Rx}} + \tau_{\text{p}}^{\text{sleep}} P_{\text{sleep}}) \Big)$$

[2] According to the CC1200 data sheet [17], $P_{\text{Tx}} = 108$ mW, $P_{\text{Rx}} = 70$ mW, and $P_{\text{sleep}} = 1.5$ μW, respectively.

$$\cdot \frac{1}{2} \frac{\tau_{\mathrm{m}}^{p}}{(\tau_{\mathrm{m}}^{\mathrm{pre}} + \tau_{\mathrm{m}}^{\mathrm{wait}})} + \tau_{\mathrm{m}}^{\mathrm{data}} P_{\mathrm{Tx}},$$

and

$$E_{\mathrm{RX}} = \left(\frac{\tau_{\mathrm{m}}^{l}}{\tau_{\mathrm{p}}^{p}} (\tau_{\mathrm{p}}^{l} P_{\mathrm{Rx}} + \tau_{\mathrm{p}}^{\mathrm{sleep}} P_{\mathrm{sleep}}) + \tau_{\mathrm{m}}^{\mathrm{sleep}} P_{\mathrm{sleep}} \right)$$

$$\cdot \frac{1}{\lambda \tau_{\mathrm{m}}^{p}} + \tau_{\mathrm{m}}^{\mathrm{pre}} P_{\mathrm{Rx}} + \tau_{\mathrm{m}}^{\mathrm{ACK}} P_{\mathrm{Tx}} + \tau_{\mathrm{m}}^{\mathrm{data}} P_{\mathrm{Rx}},$$

where $\tau_{\mathrm{m}}^{\mathrm{sleep}} = \tau_{\mathrm{m}}^{p} - \tau_{\mathrm{m}}^{l}$ and $\tau_{\mathrm{p}}^{\mathrm{sleep}} = \tau_{\mathrm{p}}^{p} - \tau_{\mathrm{p}}^{l}$.

Let $E[\text{Delay}]$ be the expected one-hop delay for a packet.

$$E[\text{Delay}] = \frac{1}{2} \tau_{\mathrm{m}}^{p} + \tau_{\mathrm{m}}^{\mathrm{data}}.$$

As described in Section III-A, we have two tunable parameters τ_{m}^{p} and τ_{p}^{p} in MAC and PHY, respectively. Given arrival rate λ, let $f(\tau_{\mathrm{m}}^{p}, \tau_{\mathrm{p}}^{p})$ be an objective function, where our goal is to minimize the energy consumption while still achieving the delay requirement. Thus, we choose $f(\tau_{\mathrm{m}}^{p}, \tau_{\mathrm{p}}^{p}) = E_{\mathrm{TX}} + E_{\mathrm{RX}}$ which represents the energy consumption of a node for transmitting and receiving a packet. Then the optimization problem can be formulated as:

$$\min_{\tau_{\mathrm{m}}^{p}, \tau_{\mathrm{p}}^{p}} f(\tau_{\mathrm{m}}^{p}, \tau_{\mathrm{p}}^{p})$$

$$\text{subject to } E[\text{Delay}] \leq \text{Delay}^{\text{Req}} \quad (1)$$

$$\tau_{\mathrm{m}}^{l} \geq 2\tau_{\mathrm{m}}^{\mathrm{pre}} + \tau_{\mathrm{m}}^{\mathrm{wait}} \quad (2)$$

$$\tau_{\mathrm{m}}^{\mathrm{wait}} \geq \tau_{\mathrm{m}}^{\mathrm{ACK}} + \tau_{\mathrm{m}}^{\mathrm{proc}} \quad (3)$$

$$\tau_{\mathrm{p}}^{\mathrm{min}} \leq \tau_{\mathrm{p}}^{p} \leq \tau_{\mathrm{p}}^{\mathrm{pre}}, \quad (4)$$

where $\text{DELAY}^{\text{Req}}$ in Eq. (1) is the one-hop delay requirement given by the application. Eq. (2) is required to receive a packet of HD-MAC preamble sent by TX when RX turns on its RF chip and Eq. (3) represents the minimum time needed to receive an ACK with the processing delay $\tau_{\mathrm{m}}^{\mathrm{proc}}$. The constraint in PHY is described in Eq. (4), which is restricted by the RF hardware, where $\tau_{\mathrm{p}}^{\mathrm{min}}$ is the minimum required time for PHY duty-cycling.

To solve the above optimization problem, we choose the minimum τ_{m}^{l} and $\tau_{\mathrm{m}}^{\mathrm{wait}}$ and the maximum τ_{p}^{p} in Eqs. (2)-(4) which obviously minimizes the objective function. Then, we can remove the constraints in Eqs. (2)-(4). Since the objective function and Eq. (1) are convex combinations of τ_{m}^{p} and τ_{p}^{p}, we can use a popular convex optimization solver technique which has been studied extensively (e.g., [22]) from which we can obtain the optimal parameters for both τ_{m}^{p} and τ_{p}^{p}.

In practice, the optimal parameters obtained above may not be applicable directly to real sensors due to some hardware constraints, such as limited clock granularity (e.g., 10 ms) and a limited set of available lengths of a PHY preamble. Thus, the obtained parameters should be adjusted, considering the hardware constraints imposed in each chip. Solving the optimization problem enables us to have the optimal τ_{m}^{p*} and τ_{p}^{p*}, such that (i) they are the closest parameters from the solution of the problem, (ii) they are available parameters of the given device, and (iii) they minimize $f(\tau_{\mathrm{m}}^{p*}, \tau_{\mathrm{p}}^{p*})$ while still achieving Eq. (1). Note that these can be the two nearest

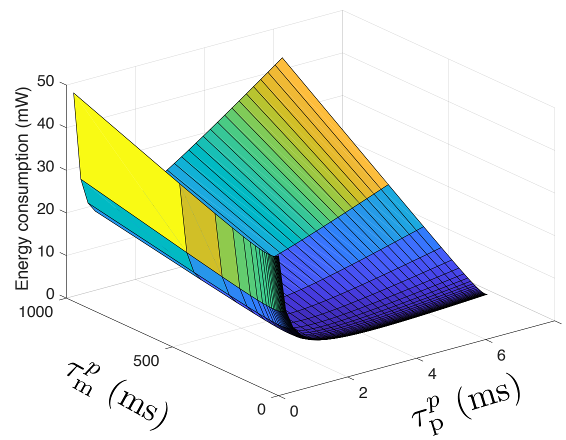


Fig. 5: Based on analysis, it plots the objective function with varying τ_{m}^{p} and τ_{p}^{p}, where $\lambda = 0.5$ packets/s. The optimal values are obtained by $\tau_{\mathrm{m}}^{p*} = 125$ ms and $\tau_{\mathrm{p}}^{p*} = 4.88$ ms.

candidates which are smaller (and greater) than or equal to the solution. Since the objective function is convex, τ_{m}^{p*} and τ_{p}^{p*} are the optimal parameters in terms of holding the hardware constraints (see Fig. 5).

C. Condition for HD-MAC-OP

We now discuss the conditions under which we switch the mode to HD-MAC-OP. Let $g(\tau_{\mathrm{p}}^{p})$ be an objective function of HD-MAC-OP given by Eq. (5), where we let $\hat{\tau}_{\mathrm{p}}^{p*}$ be an optimal parameter for $g(\tau_{\mathrm{p}}^{p})$:

$$g(\tau_{\mathrm{p}}^{p}) = \tau_{\mathrm{m}}^{\mathrm{data}} P_{\mathrm{Tx}} + \tau_{\mathrm{m}}^{\mathrm{data}} P_{\mathrm{Rx}} + \frac{\tau_{\mathrm{p}}^{l} P_{\mathrm{Rx}} + \tau_{\mathrm{p}}^{\mathrm{sleep}} P_{\mathrm{sleep}}}{\lambda \tau_{\mathrm{p}}^{p}} \quad (5)$$

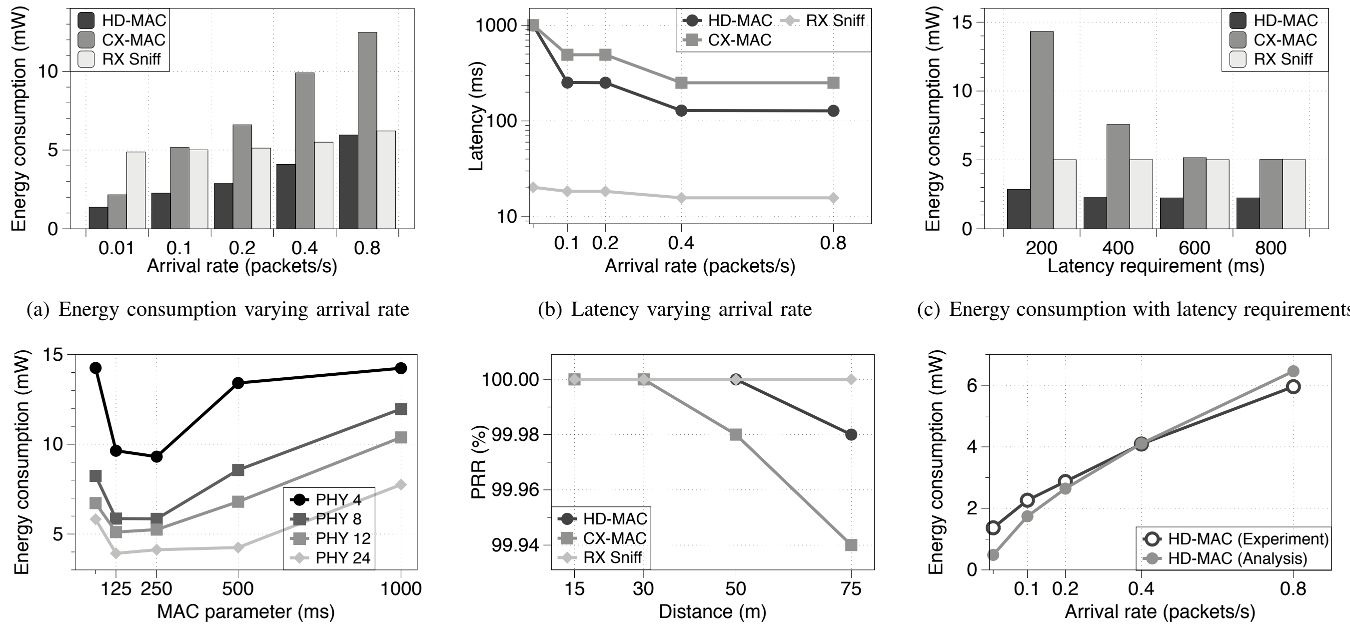
We then propose the following condition as in Eq. (6) which means that the minimum energy consumption of HD-MAC-OP is less than or equal to that of HD-MAC. Then, HD-MAC changes its mode to HD-MAC-OP to achieve better energy efficiency, if the condition is satisfied for the given λ.

$$f(\tau_{\mathrm{m}}^{p*}, \tau_{\mathrm{p}}^{p*}) \geq g(\hat{\tau}_{\mathrm{p}}^{p*}) \quad (6)$$

IV. Implementation and Evaluation

A. Implementation

We implement HD-MAC on Contiki OS [23], which is an open source operating system for IoT. To implement HD-MAC, we modify a CX-MAC driver, which is a version of X-MAC implementation [6] in the Contiki OS. Since an RF driver in the Contiki OS does not support RX Sniff (i.e., PHY duty-cycling) for CC1200 [17], we extend the current RF driver to work with RX Sniff. For real implementation and experiments, we use Firefly motes [20] which are equipped with CC1200 RF chip. To evaluate the performances of HD-MAC, we perform extensive experiments in an office environment in comparison with CX-MAC (MAC duty-cycling) and RX Sniff (PHY duty-cycling).



(a) Energy consumption varying arrival rate

(b) Latency varying arrival rate

(c) Energy consumption with latency requirements

(d) Impact of parameters of MAC and PHY

(e) Reliability varying distance

(f) Validation of analysis

Fig. 6: Evaluation result of HD-MAC under various environments. Standard deviations for each evaluation are omitted due to too small values. The optimal MAC and PHY parameters are chosen for the given environments.

B. Peer-to-peer Evaluation

Evaluation setup. We measure current consumption of a Firefly mote using Power monitor [24] so as to evaluate the real energy consumption of HD-MAC. Since the current consumption measured by a power monitor includes not only that of the RF chip but also those of an MCU and peripheral devices, we calibrate the power consumption of the mote[3], which only represents the power consumption of the RF chip.

Performance metrics of our evaluation are energy consumption, latency, and reliability with varying arrival rate λ for a Poisson distribution, distances, and latency requirements. The energy consumption is measured by the summation of the calibrated energy consumption for both TX and RX per unit time. The latency is calculated by averaging the time between packet generation at TX and packet reception at RX. Reliability is measured by PRR (Packet Reception Ratio), which is the number of received packets divided by the total number of transmitted packets.

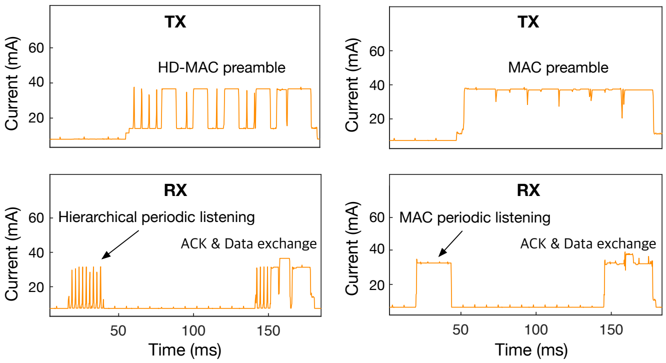
Energy efficiency and latency. Fig. 6(a) demonstrates the energy consumption of HD-MAC, CX-MAC, and RX Sniff, where arrival rates vary from 0.01 to 0.8 packets/s. Following our analytic results, we choose the optimal MAC and PHY parameters for the given arrival rate. Note that we also choose the optimal parameter for a fair comparison in CX-MAC and RX Sniff, which shows the minimum energy consumption. Our result shows that HD-MAC can reduce energy consumption up to 72% compared with others. The latency performance with the optimal parameters is shown in Fig. 6(b). Although RX Sniff shows the best latency performance due to the omitted MAC preamble and ACK, it consumes more energy especially for low arrival rates. HD-MAC shows better latency performance than that of CX-MAC, since the optimal MAC parameter of HD-MAC, which directly impacts on the latency performance, can be shorter than that of CX-MAC.

Fig. 6(c) shows the energy consumption while achieving the given latency requirements, where $\lambda = 0.1$. Since strict latency requirements hinder choosing a long MAC parameter, CX-MAC consumes a lot of energy, but HD-MAC's energy efficiency is still much better than the others because of our proposed hierarchical duty-cycling. Experimental impacts of MAC and PHY parameters for the energy consumption with $\lambda = 0.4$ are shown in Fig. 6(d), where x-axis represents τ_{m}^{p} and each line is for different τ_{p}^{p}.

Reliability and validation of analysis. Fig. 6(e) shows the reliability performance through PRR. Using different distances from 15 to 70 m, we measure PRR of 1000 packets with 5 repetitions for each protocol. The result indicates that HD-MAC does not incur any loss of reliability performances, evidenced by the similar PRR performances compared to the others. We also validate our analysis through experiments (see Fig. 6(f)). It demonstrates that the energy consumption measured by the real sensor mote and from the analysis shows the same tendency with slight difference. Thus, it is reasonable to choose the optimal parameters based on the analysis.

Current consumption measurement. Fig. 7 shows the real current consumptions of TX and RX based on HD-MAC and CX-MAC. When we measure the current of our sensor

[3]The calibrated power consumption of the RF chip: $P_{\mathrm{Tx}}^{*} = 76.29$ mW, $P_{\mathrm{Rx}}^{*} = 70.2$ mW, and $P_{\mathrm{sleep}}^{*} = 1.5\ \mu$W with 3V.



(a) HD-MAC (b) CX-MAC

Fig. 7: Real current consumption of TX and RX using Power monitor for (a) HD-MAC and (b) CX-MAC.

board (i.e., Firefly) using Power monitor, the current not only comes from an RF chip but also includes all other devices (e.g., MCU, sensors). Thus, the measured current is higher than the calibrated power consumption; however it clearly shows different operations of both protocols. First hierarchical periodic listening is illustrated in Fig. 7(a). By applying hierarchical periodic listening, we can reduce a lot of energy consumption compared to the result in Fig 7(b), which is turned on for long time. In case of transmitting MAC preambles, HD-MAC and CX-MAC show distinct differences in terms of applied PHY duty-cycling for waiting ACK and delayed wake-up. Thus, HD-MAC also achieves energy saving in HD-MAC preamble and ACK.

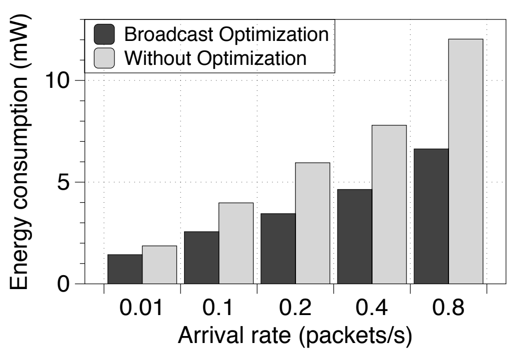


Fig. 8: Evaluation of broadcast optimization.

Broadcast optimization. We also evaluate the additional designs of HD-MAC. Fig. 8 represents the effect of the broadcast optimization, where we measure the energy consumption with broadcast traffics. Under varying arrival rates from 0.01 to 0.8 packets/s, it shows that the broadcast optimization reduces the energy consumption up to 45%. The energy savings come from turning off its RF chip once receiving HD-MAC preamble for broadcast. When the number of RXs increases, the energy efficiency of HD-MAC for broadcast traffics will be improved.

Traffic-driven mode. We also analyze the traffic-driven mode for HD-MAC. As described in Section III-C, Fig. 9 shows the

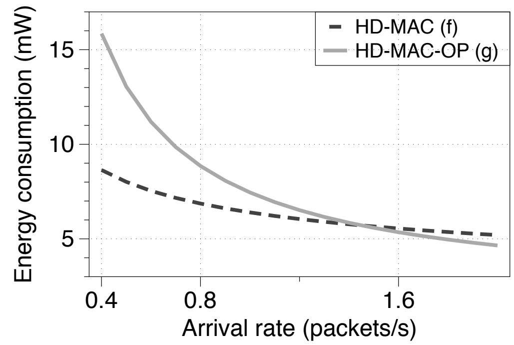


Fig. 9: Evaluation of traffic-driven mode.

condition to choose HD-MAC-OP, where we plot the energy consumption analytically based on the evaluation results and the data sheet. Under our environment, choosing HD-MAC-OP can have better energy efficiency when the arrival rate is larger than 1.5 packets/s. It denotes that for applications which generate packets more than 1.5 packets per second, using HD-MAC-OP is more energy efficient than HD-MAC with MAC duty-cycling.

C. Many-to-one Evaluation

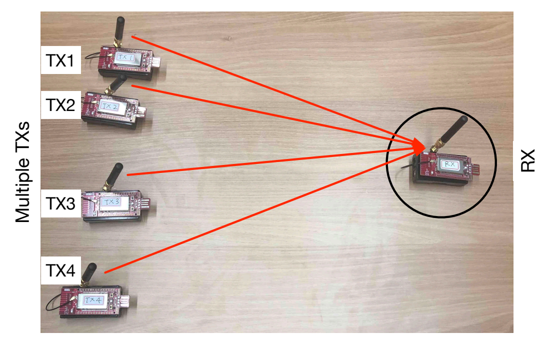


Fig. 10: Evaluation setup of our many-to-one evaluation. We use multiple TXs from 2 to 8 and 1 RX, where the figure shows the 4 TXs case. Each TX generates packets with Poisson rate λ.

Evaluation setup. As shown in Fig. 10, to evaluate HD-MAC in more generalized environments, we perform many-to-one evaluation, where multiple TXs transmit packets to 1 RX concurrently. Each TX generates packets with a Poisson rate λ which is fixed to 0.8 packets/s. By changing the number of TXs from 2 to 8, we evaluate the impact of contentions on HD-MAC compared to the others. Since collisions and contentions in wireless channels are inevitable, we use traditional CSMA/CA mechanism to avoid collisions and retransmit a packet if the packet is failed to be delivered. We choose the maximum number of retransmission as 3 or 7, since it is enough to achieve high enough reliability in our environment. As chosen in the peer-to-peer evaluation, we also measure energy efficiency, latency, and reliability in the many-to-one evaluation.

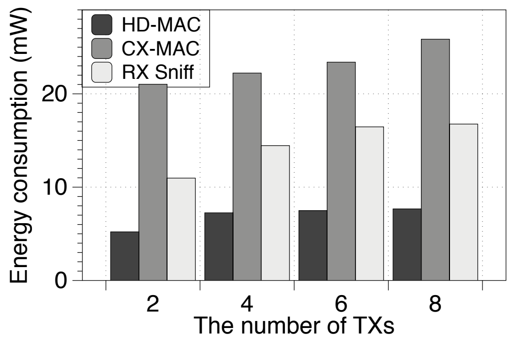
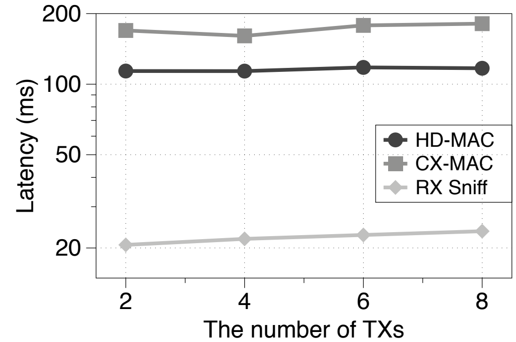


Fig. 11: Energy efficiency of the many-to-one case, where arrival rate is 0.8 packets/s.

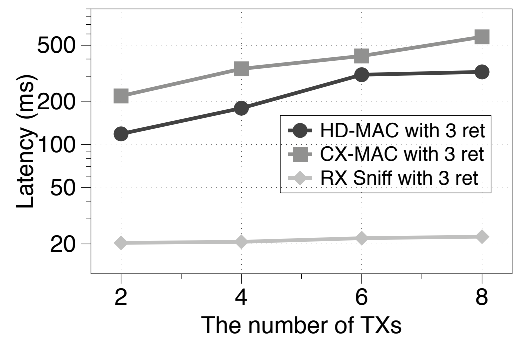
Energy efficiency. Fig. 11 shows the energy consumption of TX, which is also measured using Power monitor, when the number of TXs is varying from 2 to 8. As the number of TXs increases, it is obvious that each TX suffers from severe contentions and collisions; hence the energy consumption also increases for all protocols. Even though there are multiple TXs in contentions, HD-MAC shows the best energy efficiency compared to the others, where the energy consumption is reduced at most 75% and 54% for CX-MAC and RX Sniff, respectively. It denotes that HD-MAC is not only energy efficient in one-to-one communication, but also scalable with respect to the number of TXs.

Latency. In case of the multi-to-one communication, we also evaluate the latency performance. As mentioned earlier, we use a conventional CSMA/CA method so as to handle contentions and collisions. As shown in Fig. 12(a) and Fig. 12(b), we choose two cases, where one is without retransmission and the other is with 3 retransmissions. Since we only measure latencies of successfully delivered packets, the latency performance without retransmission is almost the same as that of the peer-to-peer case (Fig. 12(a)). In Fig. 12(b), the latency performance is degraded due to retransmitted packets as the number of TXs increases. While RX Sniff shows the best performance due to the omitted MAC preamble, HD-MAC is still better than CX-MAC because of its short HD-MAC preamble compared to that of CX-MAC.

Reliability. To evaluate how those protocols handle contentions and collisions, we measure PRR as a reliability metric. Fig. 13 shows the PRR performances of HD-MAC compared to CX-MAC and RX Sniff with 3 and 7 retransmissions. Since the amount of contentions becomes more severe when the number of TXs increases, the PRR performances also get worse for all protocols. We show that HD-MAC achieve at most 97% and 98% PRR performances with 3 and 7 retransmissions. As shown in our evaluation, the reliability performance of HD-MAC is similar to other protocols, which means that HD-MAC achieves the similar reliability performance while minimizing the energy consumption.



(a) Latency performance without retransmission



(b) Latency performance with 3 retransmissions

Fig. 12: Latency evaluation of the many-to-one case, where arrival rate is 0.8 packets/s. The latency performances are measured without and with 3 retransmissions.

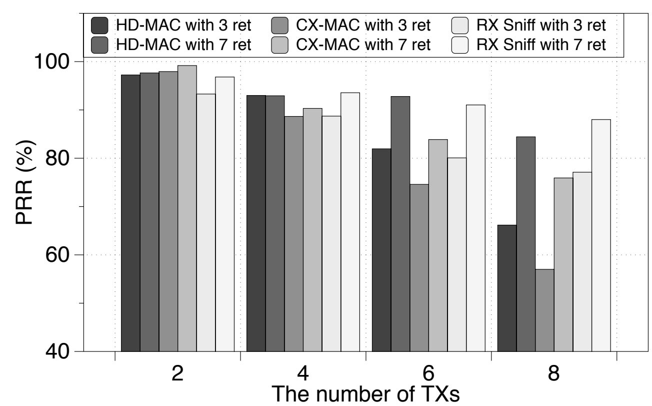


Fig. 13: Reliability of the many-to-one case, where arrival rate is 0.8 packets/s. We choose 3 and 7 retransmissions for each evaluation.

V. Discussions and Future Work

A. Robustness to Interference

In duty-cycling protocols, it is important to turn off an RF chip as much as possible to improve energy efficiency. In HD-MAC, we achieve the minimum RF on-time through hierarchical periodic listening. More specifically, since RX Sniff of CC1200 uses carrier sensing (CS) to detect the PHY preamble, it can minimize the RF on-time of PHY duty-cycling. However, it is vulnerable in the environments with external interference signals. To detect existence of the PHY preamble, CS uses RSSI (Received Signal Strength Indicator). While performing hierarchical periodic listening, when the RF chip is turned on, it measures RSSI and determines the existence of the PHY preamble by comparing the measured RSSI and a certain threshold. If the measured RSSI exceeds the threshold, the RF chip keeps listening to wireless channel to receive the PHY preamble, otherwise it is turned off. The problem is that noise signals can also make the RF chip be turned on, since RSSI of the noise signals can be high enough to be detected.

To avoid energy waste caused by such interference, HD-MAC can work with an option of so-called PQT (Preamble Quality Threshold) to determine the existence of the PHY preamble. Different from CS, PQT detects the PHY preamble based on a preamble detector in CC1200. Since the preamble detector outputs the quality of received signals, which shows high value if the signal is close to the PHY preamble, the RF chip is able to be turned on only when the PHY preamble is being transmitted. Due to the preamble detector, PQT requires a longer RF on-time than that of CS; hence choosing PQT in noiseless environments might be energy inefficient compared to choosing CS and vice versa.

B. HD-MAC with Other MAC Protocols

As mentioned earlier, HD-MAC is not limited to asynchronous X-MAC protocol, but also applicable to other MAC protocols. The key idea of HD-MAC lies in applying hierarchical listening idea, when the RF chip should be turned on. In case of synchronous MAC protocols [1], [2], [8], each node is turned on for exchanging synchronization packets. Even though the RF on-time is much shorter than that of asynchronous MAC protocols due to well-synchronized nodes, applying hierarchical listening can further reduce energy consumption.

More interestingly, when our idea is applied to partially synchronous protocols [11], [12], [14], it can save more energy than the case of synchronous protocols. In partially synchronous protocols, they reduce the cost of synchronization by infrequently performing the synchronization but compensate a small amount of clock skew. The clock compensation is normally done by turning on the RF chip for longer time compared to that of synchronous MAC protocols. Thus, applying hierarchical listening to the long time for the compensation can save a lot of energy. We will design and implement HD-MAC in partially synchronous MAC protocols as our future work.

VI. CONCLUSION

We proposed a new Hierarchical Duty-cycling MAC protocol (HD-MAC) that integrates MAC duty-cycling and PHY duty-cycling. We designed HD-MAC as a cross-layer protocol and formulated an optimization problem to choose the optimal parameters in both MAC and physical layers so as to maximize energy efficiency with a delay guarantee. We implemented HD-MAC in Contiki OS and evaluated the performance of HD-MAC. Compared with existing only MAC and PHY duty-cycling protocols, HD-MAC showed better energy efficiency while achieving delay requirement.

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