# Design and Analysis of Asynchronous Wakeup for Wireless Sensor Networks

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***Abstract*—In wireless sensor networks, scheduling the sleep duration of each node is one of the key elements for controlling critical performance metrics such as energy consumption and latency. Since the wakeup interval is a primary parameter for determining the sleeping schedule, how to tune the wakeup interval is crucial for the overall network performance. In this paper, we present an effective framework for tuning asynchronous wakeup intervals of IEEE 802.15.4 sensor networks from the energy consumption viewpoint. First, we derive an energy consumption model of each node as an explicit function of the wakeup interval, and empirically validate the derived model. Second, based on the proposed model, we formulate the problem of tuning the wakeup interval with the following two objectives: to minimize total energy consumption and to maximize network lifetime. We show that these two problems can be optimally solved by an iterative algorithm with global information by virtue of the convexity of the problem structure. Finally, as practical solutions, we further propose heuristic optimization algorithms that only exploit local information. In order to develop heuristic algorithms, we propose two broadcasting schemes, which are entitled as maximum wakeup interval broadcasting and efficient local maximum broadcasting. These broadcasting algorithms enable nodes in the network to have heterogeneous wakeup intervals.**

***Index Terms*—Sensor networks, energy saving MAC, IEEE 802.15.4 MAC, distributed optimization.**

## I. INTRODUCTION

WIRELESS sensor networks (WSNs) have been one of the most active research areas in computer and communication societies because of numerous promising applications ranging from military surveillance to environmental monitoring. In practice, efficient information sharing through wireless communication endows substantial benefits of computing and networking to many new domains.

However, in order to support these applications in a proper manner, several important issues should be resolved. One of them is the energy conservation problem of battery-operated devices, which is typical in most of application scenarios. Since replacing or recharging the battery is often difficult in practice, how to conserve the battery power is one of the most essential challenges in WSNs. A lot of research efforts have been made in various aspects, for example, voltage scaling and optimized coding [1]–[3]. From the perspective of the communication protocol, the energy efficiency of the MAC algorithm is critical since the access time for the wireless channel is determined at the MAC layer. Hence, our main focus is on the energy efficiency of the MAC protocol of WSNs.

There have been extensive studies for designing energy efficient sensor network MACs, for example, [4]–[16]. Although each of these protocols has been proposed with its own objective, their common starting point is the fact that the energy consumption for idle listening, which is needed to keep the receiving circuitry awake for possible packet reception, is a major source of current drain [4]. Thus, most existing algorithms adopt a periodic interval consisting of a short active duration and a long inactive one to reduce idle listening. Here, this periodic interval is entitled as the *wakeup interval*.

In this paper, we propose an effective framework for an asynchronous MAC in order to reduce the power consumption of a WSN. In particular, our contributions are as follows:

- First, in order to quantify the network-wide energy consumption, we introduce the notion of the active ratio, which is defined as the average active period per unit time. Then, we derive an explicit formula for the active ratio in terms of the wakeup interval. [1] We empirically validate the proposed power consumption model by using a testbed with Micaz [17], which is one of the most popular WSN devices.
- Second, based on the proposed power consumption model, we formulate the problem of tuning the wakeup interval of each node with the following two objectives: to minimize total energy consumption and to maximize network lifetime. We show that these two optimization problems can be solved by an iterative algorithm with global information by virtue of the convexity of the problem structure.
- Finally, based on the observation that the homogeneous wakeup interval incurs considerable overhead, we propose two broadcasting algorithms, i.e., maximum wakeup interval broadcasting (MWB) and efficient local maximum broadcasting (ELB), in order to enable each node to have a different wakeup interval. With MWB and ELB, we first propose centralized update algorithms for heterogeneous wakeup intervals. Then, for improved scalability,

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[1] In our analysis, we use the standard frame formats and parameters of IEEE 802.15.4 [18], the international standard for low-rate and low-power wireless networks.

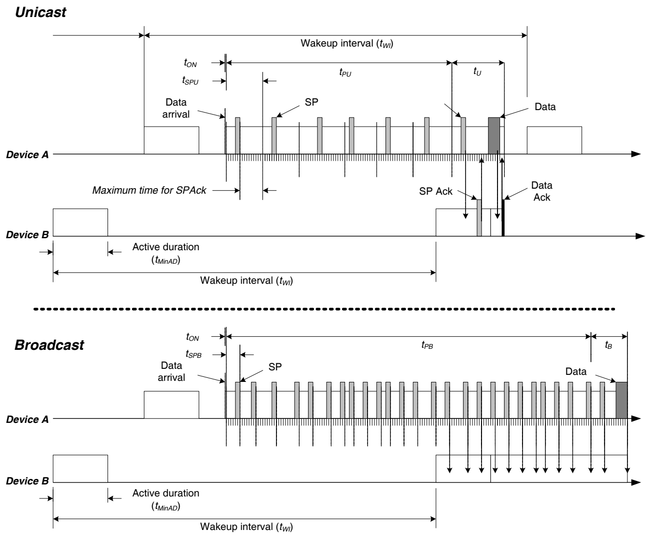


Fig. 1. Example timelines of LPEA. Unicast: Device A transmits a frame to Device B. Broadcast: Device A broadcasts a frame.

we further propose localized algorithms, which achieve competitive performance.

According to how to schedule the active duration of network nodes, existing MAC algorithms can be divided into two classes: synchronous and asynchronous. In the synchronous MACs such as SMAC [4], each node basically wakes up and sleeps at the same time by a certain synchronization algorithm. Since every node shares a common active duration, frames can be exchanged during this duration. However, a synchronization algorithm requires extra time for exchanging control frames. In addition, there is a significant scaling problem with a synchronous approach since synchronization becomes more difficult as the network size increases.

On the other hand, a node with an asynchronous MAC such as BMAC [10], follows its own schedule without synchronization with other nodes. Since there is no synchronization effort, asynchronous MACs are relatively simple, and can maintain a smaller active duration than synchronous MACs. However, when a transmitter tries to send a frame to a receiver following a different schedule, the transmitter has to keep spending energy until the receiver wakes up. In general, an asynchronous approach is more energy efficient than a synchronous one when traffic load is low [10].

The performance of asynchronous MACs is usually determined by two MAC layer parameters, i.e., the active duration and the wakeup interval. Figure 1 illustrates these two notions in detail. The active duration is the time period of how long a device wakes up for frame reception in each wakeup interval. For example, FG-MAC [13] focuses on minimizing the active duration, which dominates energy consumption of low-traffic nodes. However, it should be noted that the active duration is usually determined at the time of protocol design and remains fixed afterwards. In the meantime, the wakeup interval determines how often a device wakes up. Unlike the active duration, the wakeup interval can be adjusted by considering various factors such as network traffic and topology after protocol design.

In order to show the relation between the wakeup interval and network performance, network energy consumption has been discussed with analytical models in [11] and [12]. In [19], an approximation model from simulation in a star topology was presented. Nevertheless, these existing studies focused on transmission of unicast frames only. To the best of our knowledge, there has been few studies on the network-wide energy consumption of asynchronous MACs with broadcasting traffic.

The rest of the paper is organized as follows. In the next section, existing sensor network MACs are introduced. Then, we derive and empirically validate an analytical model for the active ratio in Section III. Based on the proposed model, the optimal wakeup interval is studied in Section IV. Then, we discuss the heterogeneous wakeup interval by introducing two broadcasting algorithms in Section V. Our simulation study follows in Section VI. Finally, we conclude our paper in section VII.

## II. Preliminaries: MAC Protocols for Wireless Sensor Networks

In this section, we provide an overview of MAC protocols for WSNs, which will be preliminaries for our work. As briefly introduced in the previous section, sensor network MACs can be classified into two groups, i.e., synchronous and asynchronous ones. Among the synchronous MACs, SMAC is one of the most widely known protocols [4]. In SMAC, each node keeps the same schedule, which consists of alternating active and inactive durations. The active duration starts with a sub-duration for SYNC frames, followed by a sub-duration for request-to-send (RTS) frames. Thus, when a node enters into the sub-duration for SYNCs, it transmits a SYNC with a predefined probability. Whenever a node receives a SYNC, it adjusts its own timer. Then, in the sub-duration for RTSs, a node with a data frame transmits an RTS. If a node receives an RTS, it replies with a clear-to-send (CTS) frame. After the sub-duration, a relatively long inactive duration follows. If a node did not transmit RTS or receive CTS during the previous active duration, it turns off the radio circuitry and saves energy during this inactive duration. However, if a node was involved in the RTS/CTS transmission, it stays awake to exchange the scheduled data frame in the inactive duration.

However, the relatively long inactive duration of SMAC introduces the problem of increased latency. This issue has been well studied in [20]. DSMAC was proposed to reduce the latency of SMAC [5]. Based on the same framework, DSMAC divides the wakeup interval in a dynamical manner. Another MAC protocol, TMAC, has also been proposed to reduce the latency by reserving the channel by an RTS frame [6]. A fast path scheduling algorithm has been proposed in [7] to reduce latency by exploiting the inactive duration. An aligning algorithm for the active duration was proposed in DMAC through a data-gathering tree [8].

On the other hand, BMAC is one of the most well-known asynchronous MACs [10]. It transmits a frame with a long preamble followed by actual data. If the receiver recognizes the preamble by periodic sampling, it stays awake in order to receive the data. In WiseMAC [14], an algorithm for reducing the length of the long preamble has been proposed based on local synchronization. The WiseMAC receiver informs the sender of its own clock by piggybacking clock information in the acknowledgement frame. Then, the sender keeps track of the receiver's clock skew and transmits a data frame with a short preamble just before the estimated wakeup time of the receiver. SCP-MAC is another hybrid MAC with a similar local synchronization method[15], which uses a two-phase contention to alleviate collision and an adaptive channel polling to handle bursty traffic. The use of short frames instead of long ones, together with an idea of a dual channel, was introduced in STEM [9]. XMAC [11] and TICER [12] further exploit a similar idea with a single channel. The dual channel idea of STEM was further extended with a wakeup radio in [21], [22]. An extensive survey on sensor network MAC algorithms can be found in [1], [23], [24].

For the rest of the paper, we focus on the general feature of asynchronous algorithms proposed in XMAC and TICER. We call this approach *Long Preamble Emulation with Acknowledgement (LPEA)*. An illustrative timeline of LPEA is introduced in Fig. 1. Here, the short frame that replaces the long preamble is called the Short Preamble (SP). In addition, the corresponding acknowledgement is called the Short Preamble Acknowledgement (SPAck). If we compare unicast transmission with broadcast one, the unicast transmission usually finishes earlier because it is acknowledged by SPAck. For broadcasting traffic, the stream of SPs is transmitted slightly longer than one wakeup interval to wake up all the neighbors.

## III. Derivation of Active Ratio

In this section, we adopt the notion of the active ratio, which is defined as the average active period per unit time [25]. [2] Although the active ratio does not distinguish transmission, reception, and idle listening, it is still a reasonable measure of energy consumption because of the following reason: In many devices, energy consumption for transmission is quite similar to that for reception (including idle listening and channel sensing), both of which are much larger than that for the standby mode [26]–[28]. [3] Here, we derive an explicit formula for the active ratio of a node as a function of the wakeup interval. [4] For tractability, we introduce the following assumptions: There are no collisions, no overhead for turning on the transceiver, and no internal delay by an operating system such as those for data copy and task queue. These assumptions are practically reasonable, especially when the traffic load is not very severe. In fact, most of energy saving MACs have been designed under these assumptions [4], [10], [11]. The definitions and the values of the parameters used in our analysis are summarized in Table I.

[2]Note that we refine the concept of the active ratio in [25] and further provide its closed-form expression for both, unicast and broadcast scenarios.

[3]For example, in cc2420, the current ratio among transmission, reception, and idle modes is 17.4:19.7:0.4.

[4]Although we focus on the active ratio that dominates the total energy consumption of a device, an inactive ratio can also be integrated in order to derive a more precise model for energy consumption. The inactive ratio can be obtained by subtracting the active ratio from one.

TABLE I
Parameters and Symbols Used for Analysis

| Symbol | Parameter | Value |
|---|---|---|
| $L_{SP}$ | Short Preamble length (Byte) | 21, (23, 24) |
| $L_{SPAck}$ | Short Preamble Ack length (Byte) | 21, (23) |
| $L_{Data}$ | Data Frame length (Byte) | 50 |
| $L_{Ack}$ | Acknowledgement Frame length (Byte) | 11 |
| $t_b$ | Transmit/Receive one byte (s) | 32E−6 |
| $t_{CCA}$ | Time to perform CCA (s) | 128E−6 |
| $t_{TR}$ | Turnaround time between Tx and Rx (s) | 192E−6 |
| $t_{ON}$ | Turn on time(s) | 192E−6 |
| $t_{slot}$ | Backoff slot time (s) | 320E−6 |
| $t_{WI,MAX}$ | Maximum Wakeup interval | 2 |
| $minBE$ | Minimum Backoff exponent | 7 |
| $t_{WI}$ | Wakeup interval | |
| $t_{MinAD}$ | Minimum Active duration | |
| $r_{TU}$ | Unicast frame transmission rate | |
| $r_{RU}$ | Unicast frame reception rate | |
| $r_{TB}$ | Broadcast frame transmission rate | |
| $r_{RB}$ | Broadcast frame reception rate | |

### A. Derivation of the active ratio as a function of the wakeup interval

Let $I_c$ and $\rho_c$ denote the current drain when a node turns on the transceiver and the active ratio of the transceiver, respectively. Similarly, let $I_o$ and $\rho_o$ denote respectively the current drain and the active ratio of other circuitry such as the micro controller. Then, the lifetime of a node with the battery capacity of $C_{battery}$ is given as

$$T_{life} = \frac{C_{battery}}{E[I_c]\rho_c + E[I_o]\rho_o}, \quad (1)$$

where $E[\cdot]$ denotes expectation. Here, we assume that the active ratio of other circuitry is not so much larger than that of the transceiver. We further assume that $E[I_c]\rho_c \gg E[I_o]\rho_o$, which is reasonable in practice. For example, the micro controllers of Micaz [17] and Telos [29] consume 5.5 mA and 2 mA for normal operation [30], [31], while the transceiver cc2420 consumes 19.7 mA even for idle listening [26]. [5] Thus, (1) can be further approximated as

$$T_{life} \approx \frac{C_{battery}}{E[I_c]\rho_c}. \quad (2)$$

From now on, we use $\rho$ instead of $\rho_c$ for notational simplicity unless otherwise mentioned. The active ratio $\rho$ is composed of the active ratio $\rho_{TX}$ for transmission activity and the active ratio $\rho_{RX}$ for reception activity. In order to derive $\rho_{TX}$, the energy consumptions for unicast and broadcast are considered separately due to their different power-consuming natures. The overall procedure is illustrated in a detailed manner in Fig. 1. Here, we consider an SP and an SPAck as new control frames. The lengths, $L_{SP}$ and $L_{SPAck}$, of the new

[5]If other circuitry of a node requires considerable current drain, $T_{life}$ requires a more complicated model. Though it is of importance to develop such a model, it is out of the scope of this paper.

frames including the physical layer header are 21 bytes. [6] In IEEE 802.15.4, the number of backoff slots before transmitting a new frame is randomly selected between 0 and $2^{minBE}-1$. Here, $minBE$ is the minimum backoff exponent, of which the default value is 3 by the standard. Therefore, the average backoff time is $(2^{minBE}-1)t_{slot}/2$. In addition, the standard defines an additional time slot before transmitting a frame to perform Channel Clear Assessment (CCA) and turnaround.

For unicast transmission in LPEA, a node has to exchange an SP and an SPAck before transmitting a data frame. Thus, when the receiver is in the active mode, the average time $E[t_U]$ to transmit a unicast frame can be obtained as

$$E[t_U] = 3(2^{minBE}-1)t_{slot}/2 + 3t_{slot} + L_{SP}t_b + L_{SPAck}t_b + L_{Data}t_b + t_{TR} + L_{Ack}t_b. \quad (3)$$

Here, an SP, an SPAck, and a data frame also require some additional amount of time for backoff and CCA. Thus, these terms are multiplied by three. Note that an Ack is transmitted without performing CCA. Thus, for an Ack, only the turnaround time is counted in 3. [7]

However, because of the asynchronous schedule, the sender may transmit a stream of SPs before the active time of the receiver. Specifically in the stream, the next frame is transmitted after waiting for the maximum time for an SPAck, which is equal to $(2^{minBE}-1)t_{slot} + t_{slot} + L_{SPAck}t_b$. Additionally, on average, a time duration of $(2^{minBE}-1)t_{slot}/2 + t_{slot}$ is required for random backoff and CCA before transmission of the SP. Consequently, in order to derive the length of the SP stream, we first define $E[t_{SPU}]$ as the average time for transmitting one SP for unicast as follows:

$$E[t_{SPU}] = \frac{3}{2}(2^{minBE}-1)t_{slot} + 2t_{slot} + (L_{SP}+L_{SPAck})t_b,$$

where the average waiting time before transmission is equal to that of $L_{SPAck}t_b$ and the waiting times. Then, the average time $E[t_{PU}]$ of the SP stream for unicast is given as

$$E[t_{PU}] = \left\lceil \frac{t_{WI}}{E[t_{SPU}]} \right\rceil \frac{E[t_{SPU}]}{2}, \quad (4)$$

where $t_{WI}$ is the wakeup interval of each node.

Similarly, average times for broadcast are derived as

$$E[t_B] = (2^{minBE}-1)t_{slot} + 2t_{slot} + t_{TR} + (L_{SP}+L_{Data})t_b. \quad (5)$$

$$E[t_{SPB}] = (2^{minBE}-1)t_{slot}/2 + t_{slot} + L_{SP}t_b + t_{TR}. \quad (6)$$

$$E[t_{PB}] = \left\lceil \frac{t_{WI}}{E[t_{SPB}]} \right\rceil E[t_{SPB}]. \quad (7)$$

Note that here are no SPAck and Ack for broadcasting. Thus, the number of backoff and CCA required for (5) and (6) are two and one, respectively. In (7), a sender should transmit SPs slightly longer than one wakeup interval in order to wake up every neighbor because there is no SPAck to stop SP transmission. Thus, $E[t_{PB}]$ becomes almost twice of $E[t_{PU}]$.

With (3), (4), (5) and (7), the active ratio $\rho_{TX}$ for transmission activity is derived with the unicast frame transmission rate $r_{TU}$ and the broadcast frame transmission rate $r_{TB}$ as

$$\rho_{TX} \approx r_{TU}\left(t_{ON} + E[t_{PU}] + E[t_U]\right) + r_{TB}\left(t_{ON} + E[t_{PB}] + E[t_B]\right), \quad (8)$$

where $t_{ON}$ is the time to turn on the transceiver before starting backoff for the first SP.

The active ratio $\rho_{RX}$ for reception activity consists of periodic wakeup, unicast reception, and broadcast reception. In LPEA, each node has to be turned on in a periodic manner in order to receive at least one SP. Thus, the maximum time gap between two SPs is obtained when the maximum backoff is performed for an SP. Hence, the minimum active duration, $t_{MinAD}$, can be obtained as

$$t_{MinAD} = t_{ON} + 2(2^{\min BE}-1)t_{slot} + 2t_{slot} + 2L_{SP}t_b + L_{SPAck}t_b, \quad (9)$$

where $t_{ON}$ is the time to turn on the transceiver.

For a receiver, the active time for receiving a unicast frame is $E[t_U]$ since, when it receives an SP, it terminates the SP stream with the SPAck and receives a data frame. However, in the case of broadcast, a receiver receives SPs for $E[t_{PB}]/2$ on average. Hence, by considering the unicast frame reception rate $r_{RU}$ and the broadcast frame reception rate $r_{RB}$, the active ratio $\rho_{RX}$ for reception activity is derived as

$$\rho_{RX} \approx \frac{t_{MinAD}}{t_{WI}} + r_{RU}E[t_U] + r_{RB}\left(\frac{E[t_{PB}]}{2} + E[t_B]\right) - r_{TU}E[t_{OTU}] - r_{RU}E[t_{ORU}] - (r_{TB}+r_{RB})\,t_{MinAD}, \quad (10)$$

where $E[t_{OTU}]$ and $E[t_{ORU}]$ are the average overlapped times of the periodic active durations corresponding to unicast transmission and reception. Their derivations are given in the appendix. From (8) and (10), the overall active ratio of a node is obtained as

$$\begin{aligned}\rho =& \rho_{TX} + \rho_{RX}\\ =& \frac{t_{MinAD}}{t_{WI}} + r_{TU}\left(t_{ON} + E[t_{PU}] + E[t_U] - E[t_{OTU}]\right)\\ &+ r_{TB}\left(t_{ON} + E[t_{PB}] + E[t_B] - t_{MinAD}\right)\\ &+ r_{RU}\left(E[t_U] - E[t_{ORU}]\right)\\ &+ r_{RB}\left(\frac{E[t_{PB}]}{2} + E[t_B] - t_{MinAD}\right). \end{aligned} \quad (11)$$

We further approximate (11) for tractability in our analysis. To this end, $E[t_{PU}]$ and $E[t_{PB}]$ are approximated with $t_{WI}/2$ and $t_{WI}$, respectively. These approximation are acceptable when $t_{WI}$ is expected to be greater than $E[t_{SPB}]$ and $E[t_{SPU}]$. We also ignore the times used to compensate overlapped time durations, which is reasonable as long as $t_{WI}$ is quite larger than $t_{MinAD}$, and transmission rates are not so high. Hence, $\rho$ in (11) further becomes

$$\rho \approx \frac{t_{MinAD}}{t_{WI}} + r_{TU}\left(t_{ON} + \frac{t_{WI}}{2} + E[t_U]\right)$$

[6]For compatibility, we implement the frames as broadcast data frames in the MAC layer. Then, in the payload of the MAC layer, we add 4 bytes for control fields and the destination address. Therefore, the frames consist of 6 bytes of physical layer headers, 9 bytes of MAC layer headers, 4 bytes of MAC layer payloads, and 2 bytes of frame check sequence. If the frame is implemented as a new frame in IEEE 802.15.4 with reserved bits, the length will be 15 bytes. In case of implementing as a new command frame, the length will be 18 bytes.

[7]The turnaround time $t_{TR}$ is the amount of time required for state transition between the reception mode and the transmission mode of a physical device, which is given as 192 us in 2.4 GHz channels of IEEE 802.15.4.

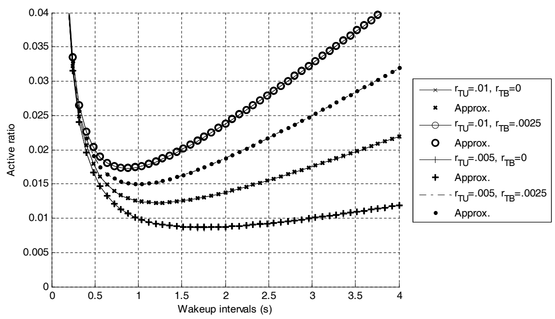


Fig. 2. Accuracy of the approximate active ratio with different transmission rates.

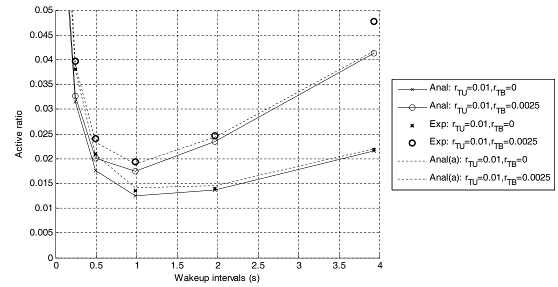


Fig. 3. Comparison of the proposed model of the active ratio with experimental results.

$$+ r_{TB}\left(t_{ON} + t_{WI} + E[t_B]\right) + r_{RU}E[t_U] + r_{RB}\left(\frac{t_{WI}}{2} + E[t_B]\right). \qquad (12)$$

In order to show the effectiveness of (12), we will give an empirical comparison between (11) and (12) in the following subsection.

### B. Model validation

In order to validate the proposed analytical model, we implement LPEA on Micaz [17], embedding cc2420 as a transceiver [26]. We use the functions of MAC primitives and the software engine provided by the transceiver manufacturer. All frames follow the format defined in IEEE 802.15.4 Standard. For the SP and the SPAck, we use the data frame without violating the standard. In order to define control frames, we add 4 bytes for control fields and the destination address. In order to compare active ratios, we construct a star topology. We vary the value of the wakeup interval from 123 ms to 3.9 s, which corresponds to the standard beacon interval in the beacon mode of IEEE 802.15.4. Each experiment is performed for 800 seconds.

First, we show the effectiveness of the approximate model in (12). Figure 2 shows the comparison between (11) and (12) with different transmission rates. For all cases, it can be verified that the approximate model matches the model in (11) very well. Now, we compare the experimental results with the analytical ones in Figure 3. In all cases, these two results agree quite well. Only when the wakeup interval is quite small, the active ratios from experiments are little higher than those from analysis. This is mainly due to the overhead of the real system. In our implementation, each device requires additional processing delay to transmit a frame. Thus, the receiver requires more time than $t_{MinAD}$ used in the analysis (7.328 ms). Thus, we empirically determine the margin, and set the minimum active duration to 9 ms for stable communication. We also present the adjusted analytical results marked 'Anal(a)' gathered from (12) with the adjusted active duration value of 9 ms. The adjusted analytical results are well matched with the experimental results.

## IV. Analysis of Optimal Wakeup Interval: The Homogeneous Case

In this section, we derive the optimal wakeup interval when every node uses a common wakeup interval $t_{WI}$. Note that the schedule of each node runs asynchronously. Since the active ratio is a function of $t_{WI}$, the lifetime of each node is directly controllable by $t_{WI}$. Hence, $t_{WI}$ should be carefully chosen to improve the overall network performance.

Here, we consider, respectively, the following two objectives: *(i)* to minimize energy consumption and *(ii)* to maximize time for network partition[33]. The former focuses on how to minimize energy consumption of the network. In this case, we can minimize the number of battery replacements of the network in an accessible location. The latter is suitable for mission-critical applications such as the battle field monitoring. The optimal value in this case corresponds to the maximum lifetime of the network without partition or a dead node. To formulate optimization problems with these objectives, we rearrange (12) by considering individual transmission and reception with subscript of $i$ as

$$\begin{aligned} f_i(x) = \frac{t_{MinAD}}{x} &+ \left(\frac{r_{TU,i}}{2} + r_{TB,i} + \frac{r_{RB,i}}{2}\right)x \\ &+ r_{TU,i}\left(t_{ON} + E[t_U]\right) + r_{TB,i}\left(t_{ON} + E[t_B]\right) \\ &+ r_{RU,i}E[t_U] + r_{RB,i}E[t_B], \end{aligned} \qquad (13)$$

where $x$ and $f_i(x)$ denotes $t_{WI}$ and $\rho$ of node $i$, respectively. Then, the first optimization problem of minimizing energy consumption is formulated as

$$\min J(x) := \sum_{i=1}^{N} f_i(x), \qquad (14)$$

$$\text{subject to } t_{baseActiveDuration} \leq x \leq t_{WI,MAX},$$

where $N$ is the number of nodes in the network, and $t_{WI,MAX}$ is the maximum-possible wakeup interval, which is determined by the latency requirement of the network. Thus, if nodes have wakeup intervals smaller than $t_{WI,MAX}$, we assume that end-to-end latency of the network satisfies the latency requirement. Since $t_{MinAD}$ is positive, we have $\partial^2 f_i(x)/\partial x^2 > 0$ from (13) and thus $f_i(x)$ is convex. Since a sum of convex functions is convex, $J(x)$ is also convex. Consequently, when $t_{baseActiveDruation}$ is zero and $t_{WI,MAX}$ is large enough, the optimal value of $x$, denoted by $x^*$, can be obtained as

$$x^* = \sqrt{\frac{2Nt_{MinAD}}{\sum_{i=1}^{N}\left(r_{TU,i} + 2r_{TB,i} + r_{RB,i}\right)}}. \qquad (15)$$

With the second objective function, i.e., to maximize the network partition time, the problem can be formulated as minimizing energy consumption of the most energy-consuming node in the following manner.

$$\min J(x) := \max\left(f_1(x), f_2(x), ..., f_N(x)\right)$$
$$\text{subject to } t_{baseActiveDuration} \leq x \leq t_{WI,MAX}. \quad (16)$$

Unlike (14), which gives a closed-form solution as shown in (15), an explicit solution for (16) can not be derived in general. However, since a maximum of convex functions is convex [34], $J(x)$ in (16) is convex. With the convexity of the objective function and the feasible region, the uniqueness of the solution is guaranteed and it can be efficiently obtained in an iterative manner [34].

In order to further understand the problem structure of (15), we consider the case of two nodes in the network. Let $A_i := r_{TB,i} + (r_{TU,i} + r_{RB,i})/2$ and $B_i := r_{TU,i}\,(t_{ON} + E[t_U]) + r_{TB,i}\,(t_{ON} + E[t_B]) + r_{RU,i}E[t_U] + r_{RB,i}E[t_B]$. Without loss of generality, let $A_1 \geq A_2$. If we let $x^c = (B_2 - B_1)/(A_1 - A_2)$, then the solution to (16) for the case of two nodes is given as $x^* = t_{baseActiveDuration}$ with $J(x^*) = f_1(x^*)$ when $x^c \leq t_{baseActiveDuration}$. Otherwise, $x^* = t_{baseActiveDuration}$ with $J(x^*) = f_2(x^*)$.

## V. Analysis of the Optimal Wakeup Interval: The Heterogeneous Case

In the previous section, we showed that the optimal wakeup interval for each formulation reduces energy consumption and improves network lifetime, respectively. However, if traffic load is nonuniform over the network, configuration with a common wakeup interval for every node will be inefficient in most cases. The adverse effect of nonuniform traffic could be significant especially when the traffic from leaf nodes funnels towards a sink node [16]. Therefore, it is desirable to allow heterogeneous wakeup intervals to further improve network performance.

However, there exists a practical problem with heterogeneous wakeup intervals. As discussed in the previous section, when a node starts transmitting an SP for broadcast, the length of the SP stream relies on the wakeup interval. If every node has a different wakeup interval, the broadcasting transmitter needs to wait long enough to wake up all the neighbors. Consequently, in order to allow heterogeneous wakeup intervals, an efficient broadcast algorithm becomes essential.

In this section, we first propose two broadcast algorithms: Maximum Wakeup interval Broadcasting (MWB) and Efficient Local Maximum broadcasting (ELM). Then, we derive active ratio models for these algorithms, which are extended versions of (12). With the derived models for broadcast, we formulate optimization problems in a similar manner as in Section IV. We further propose two heuristic algorithms for solving the optimization problems in a localized manner.

### *A. Maximum wakeup interval broadcasting and efficient local maximum broadcasting*

Two proposed algorithms for broadcasting are illustrated in Fig. 4. Maximum Wakeup interval Broadcasting (MWB) uses the maximum value of the wakeup interval allowed in the network. Since the maximum value, $t_{WI,MAX}$, is the constraint imposed on the network, if a node transmits SPs longer than

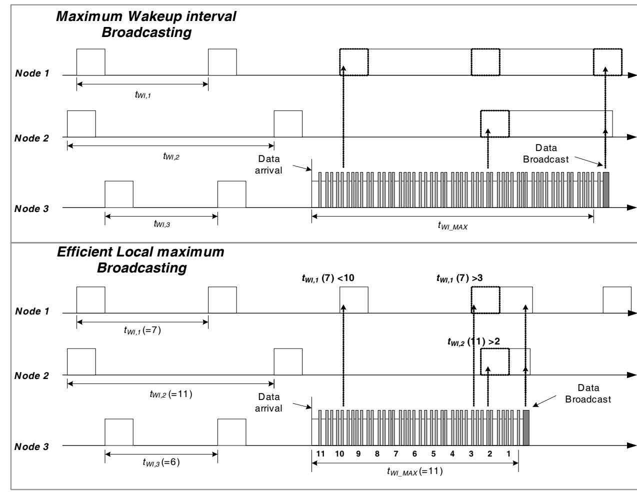


Fig. 4. Example timelines of two broadcasting methods. Node 3 broadcasts a frame.

$t_{WI,MAX}$, the stream wakes up all the neighbors, and the data can be successfully transmitted. MWB is favorable to nodes with limited memory and processing power in virtue of its simplicity. Therefore, MWB is a reasonable solution for WSNs with low broadcast rates. However, MWB incurs non-negligible overhead as the broadcast rate increases. Unlike unicast transmission that charges most of the overhead to the transmitter, broadcast requires every neighbor to consume energy for receiving SPs until it receives a data frame. Especially, for a node with a relatively short wakeup interval, transmission and reception of SPs for the duration of $t_{WI,MAX}$ becomes an unnecessary overhead.

In order to resolve this issue, we propose Efficient Local maximum Broadcasting (ELB). In a nutshell, ELB uses the maximum wakeup interval among the neighbors, and stops transmitting SPs after the interval. To this end, information on wakeup intervals of neighbors should be available. Hence, we simply add the value of the wakeup interval in the SP and SPAck frames. ELB further saves the energy consumption of a receiver. When a given receiver has a relatively short wakeup interval while one of its neighbors has a long one, SPs for broadcasting can occupy several wakeup intervals of the receiver. If the receiver can estimate the remaining time for SPs, it can just go to sleep by following its own periodic schedule after receiving an SP, and check the channel again by its own schedule.

For this function, we add the remaining time of the SP stream in the SP frame. The value starts from the local maximum and gradually decreases. In Fig. 4, Node 2 has the longest wakeup interval. Note that the numbers for wakeup intervals are calculated as the time divided by the basic unit. For example, when the basic unit is 50 ms, 11 corresponds to 550 ms. At first, Node 3 starts with 11. After 50 ms later, Node 3 transmits SPs by changing the remaining time to 10. When, Node 1 receives the SP, it compares the value with its own wakeup interval. Since its own interval of 7 is smaller than the received remaining time of 10, it implies that Node 1 can receive SPs again in the next wakeup schedule. Thus, Node 1 goes to sleep in order to save energy. In the next duration, the remaining time in the SP is 3. Then, it stays awake until it receives the data frame.

### *B. Derivation of the active ratio under heterogeneous wakeup intervals*

Heterogeneous values for wakeup intervals among nodes cause different transmission overheads for each node. Hence, we introduce two parameters, i.e., $r_{TU,i,j}$ and $r_{RU,i,j}$. Here, $r_{TU,i,j}$ denotes the unicast frame transmission rate from node $i$ to node $j$, while $r_{RU,i,j}$ denotes the unicast frame reception rate of node $i$ from node $j$. Therefore, the summation of all $r_{TU,i,j}$'s where $j$ is an element of the set $m_i$ of node $i$'s neighbors are the same as $r_{TU,i}$ used in the previous section. Also, $r_{RU,i}$ is the aggregated reception rate of $r_{RU,i,j}$'s.

First, similar to (13), the active ratio of node $i$ adopting MWB is derived as

$$\begin{aligned} f_i(\mathbf{x}_i) \approx & \frac{t_{MinAD}}{x_i} + \sum_{j \in m_i} r_{TU,i,j} \left( t_{ON} + \frac{x_j}{2} + E[t_U] \right) \\ & + \sum_{j \in m_i} r_{RU,i,j} E[t_U] \\ & + r_{TB,i} \left( t_{ON} + t_{WI,MAX} + E[t_B] \right) \\ & + r_{RB,i} \left( t_{WI,MAX} - \frac{x_i}{2} + E[t_B] \right), \end{aligned} \tag{17}$$

where $\mathbf{x}_i$ is defined as the set of wakeup intervals of node $i$ and its neighbors, i.e., $\mathbf{x}_i := \{x_j \mid j \in m_i\} \cup \{x_i\}$. Compared with (13), $r_{TU,i,j}$ is multiplied by $x_j/2$ instead of $x/2$ since unicast relies on the wakeup interval $x_j$ of the receiver $j$. For broadcast transmission, $x$ in (13) is replaced with $t_{WI,MAX}$, and multiplied by $r_{TB,i}$. For broadcast reception, $t_{WI,MAX}$ is subtracted by $x_i/2$ because a receiver detects the SP stream by asynchronous active durations after half of its own wakeup interval on average.

For the analysis of ELB, let $g_i(\mathbf{x}_{-i})$ denote the maximum wakeup interval among all the wakeup intervals of node $i$'s neighbors as follows:

$$g_i(\mathbf{x}_{-i}) = \max_{j \in m_i} x_j, \tag{18}$$

where $\mathbf{x}_{-i}$ is defined as the set of wakeup intervals of node $i$'s neighbors, i.e., $\mathbf{x}_{-i} := \{x_j \mid j \in m_i\}$. By using (18), the active ratio of ELB is derived as

$$\begin{aligned} f_i(\mathbf{x}_i) \approx & \frac{t_{MinAD}}{x_i} + \sum_{j \in m_i} r_{TU,i,j} \left( t_{ON} + \frac{x_j}{2} + E[t_U] \right) \\ & + \sum_{j \in m_i} r_{RU,i,j} E[t_U] + r_{TB,i} \left( t_{ON} + g_i(\mathbf{x}_{-i}) + E[t_B] \right) \\ & + r_{RB,j} \left( \frac{x_i}{2} + E[t_B] \right). \end{aligned} \tag{19}$$

For broadcast transmission, $g_i(\mathbf{x}_{-i})$ is multiplied by $r_{TB,i}$ instead of $t_{WI,MAX}$ in (17). In the case of broadcast reception, $x_i/2$ is added because a receiver stays awake only when the remaining time is greater than its own wakeup schedule.

### *C. Global optimization of heterogeneous wakeup intervals*

Here, we propose a global optimization framework for minimizing the network energy consumption and maximizing the network lifetime, respectively. Though these formulations provide theoretical optimal solutions, they also require substantial overhead caused by information exchange among nodes. Thus, as practical solutions, we also propose localized heuristic algorithms in the next subsection.

Similarly as in (14) and (16), where each node maintains a heterogeneous wakeup interval $x_i$, the objective functions for minimizing the energy consumption of a network and for maximizing the network lifetime are given, respectively, as follows:

$$\min J(\mathbf{x}) := \sum_{i=1}^{N} f_i(\mathbf{x}_i). \tag{20}$$

$$\min J(\mathbf{x}) := \max \left( f_1(\mathbf{x}_1), f_2(\mathbf{x}_2), ..., f_N(\mathbf{x}_N) \right). \tag{21}$$

Here, $\mathbf{x}$ is the set of wakeup intervals of all the nodes, i.e., $\mathbf{x} := \{x_1, x_2, \ldots, x_N\}$ and $f_i(\mathbf{x}_i)$ is the active ratio defined as a function of $\mathbf{x}_i$ in either (17) or (19). In case of (17), we have $\partial^2 f_i / \partial x_i^2 > 0$ and $\partial^2 f_i / \partial x_i \partial x_j = 0$, $i \neq j$. Hence, the Hessian of $f_i$ in (17) is positive definite, which is a sufficient condition for the convexity of $f_i$ in $\mathbf{x}$. In a similar manner, in case of (19), all the terms except $g_i(\mathbf{x}_{-i})$ are convex in $\mathbf{x}$ by inspection. Since the maximum of convex functions is convex [34], $g_i(\mathbf{x}_{-i})$ is also convex. Thus, $f_i$ in (19) is convex because the sum of convex functions is convex. Hence, again by using the fact that the sum and the maximum of convex functions are convex, $J(\mathbf{x})$ in (20) and (21) are both convex, which guarantees that a local minimum is the global minimum. Thus, with the convexity, the problems can be iteratively solved with the polynomial complexity with respect to the dimension of the problem space [34].

In order to further enhance the understanding of the problem structure, we consider the case of two nodes in the network. Here, we only work out the solution with MLB since that with ELB can be obtained in a similar manner. For (20), we can calculate the partial derivative of $f_1$ and $f_2$ with respect to $x_1$ and $x_2$ by using (17). The solution to (20) is given as $x_i^* = x_i^c$ if $r_{TU,j,i} \geq 2 r_{RB,i}$ where $x_i^c = \sqrt{t_{minAD}/(r_{TU,j,i}/2 - r_{RB,i})}$ and $\{i,j\} = \{1,2\}$. Otherwise, the solution regenerates into $x_i^* = x_{max}$. For (21), it is not a simple task to derive a closed-form solution even for the case of two nodes because of the nonlinear operation of maximization in $J(\mathbf{x})$.

### *D. Local optimization of heterogeneous wakeup intervals*

Global optimal solutions become meaningful either for offline calculation after traffic and topology estimation, or for online computation with frequent information exchange. However, in practice, there exist many cases when both conditions are not met. Thus, we propose two localized heuristic algorithms, which run at each node with local information only.

The first algorithm minimizes the energy consumption of a node and its one-hop neighbors. Intuitively, when a node changes its wakeup interval, the energy consumptions of the node and its neighbors will be affected. Thus, the first algorithm estimates the variation in the summation of the energy consumptions before changing its wakeup interval. If the variation is expected to be negative, it will actually update

**Algorithm 1** Local heuristic algorithm to minimize energy consumption.

$x_i \leftarrow t_{WI,MAX}$
**loop**
  $h_i(\delta) \leftarrow t_{MinAD}\left(\frac{1}{x_i+\delta} - \frac{1}{x_i}\right) + r_{RU,i}\delta.$
  **if** $h_i(\delta) < 0$ **then**
    $x_i \leftarrow x_i - \delta$
  **else**
    $x_i \leftarrow x_i + \delta$
  **end if**
**end loop**

its wakeup interval. In order to estimate the variation, we define a local variation function $h_i(\delta)$ as

$$h_i(\delta) = t_{MinAD}\left(\frac{1}{x_i+\delta} - \frac{1}{x_i}\right) + r_{RU,i}\delta. \quad (22)$$

If we assume a small change of $\delta$ in $x_i$ does not affect the local maximum wakeup intervals, the variation in the energy consumption of node $i$ is given as $t_{MinAD}\,(1/(x_i+\delta) - 1/x_i)$. In a similar manner, the variation in the energy consumption of neighbor nodes is given as $\sum_{j\in m_i} r_{TU,j,i}\delta$. Since $\sum_{j\in m_i} r_{TU,j,i}$ is equal to $r_{RU,i}$, the function $h_i(\delta)$ corresponds to the sum of the variation in the energy consumption of node $i$ and its neighbors. The overall update algorithm for $x_i$ by using (22) is given in Algorithm 1.

The second algorithm minimizes the energy consumption of the most energy-consuming node among the node itself and its neighbors. However, there are two issues with this approach. First of all, comparison of energy consumption is required for every node to find the most energy-consuming node. In addition, for a given node, adjusting its own wakeup interval may not be helpful if the node with the local maximum wakeup interval does not transmit a packet to the corresponding node. In many WSNs, where data-gathering trees are used to forward data to the sink, the following two conditions are often met: *(i)* a node that has a closer level to the sink has higher traffic, and *(ii)* most unicast transmissions are uplink and therefore affected by the wakeup interval of the parent node [16]. Then, we define the second local function, $q_i(\mathbf{x})$, with a set $m_i^c$ of children of node $i$ as

$$q_i(\mathbf{x}) = \max_{j\in m_i^c} f_j(\mathbf{x}). \quad (23)$$

Here, information on $f_j(\mathbf{x})$ is exchanged on the payload of SP. After gathering $f_j(\mathbf{x})$'s, $j \in m_i^c$, if $q_i(\mathbf{x})$ is greater than the active ratio, $f_i(\mathbf{x})$, then the node decreases its own wakeup interval by a small amount of $\delta$ $(= 0.05)$ to help higher energy-consuming children nodes. If $q_i(\mathbf{x})$ is less than $f_i(\mathbf{x})$, it increases the wakeup interval by $\delta$ $(= 0.05)$. By iteration, node $i$ is expected to decrease its maximum energy consumption as well as that of its children.

## VI. Simulation Study

In this section, we carry out a simulation study to show the performance of the proposed global and local optimization algorithms.

**Algorithm 2** Local heuristic algorithm to maximize network lifetime.

**loop**
  *update* $\mathbf{x_j}$
  *update* $f_j(\mathbf{x_j})$
  $q_i(\mathbf{x}) \leftarrow \max_{j\in m_i^c} f_j(\mathbf{x_j}).$
  **if** $q_i(\mathbf{x}) > f_i(x_i)$ **then**
    $x_i \leftarrow x_i - \delta$
  **else**
    $x_i \leftarrow x_i + \delta$
  **end if**
**end loop**

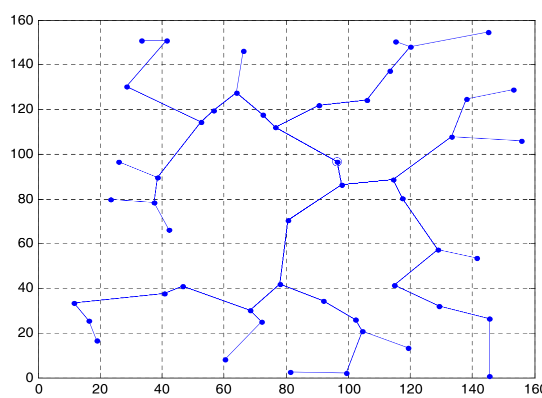


Fig. 5. Generated topology for numerical study.

### A. Performance of global optimization with homogeneous wakeup intervals

In order to show the effectiveness of the solution for global optimization with homogeneous wakeup intervals, we perform numerical analysis. We consider a 160 m by 160 m field and nodes with the transmission range of 30 m, which corresponds to typical Zigbee device specification [35]. We randomly distribute 50 nodes with uniform distribution in the field. [8] We also randomly pick a node as a sink. Then, we create a tree topology as shown in Fig. 5. The node inside a small circle is the sink and others are sensors. Each node transmits a unicast frame every 10 minutes to report sensed data, and broadcasts a frame every 20 minutes for control purpose. We assign each node the same packet generation rate. However, it should be noted that, as intermediate nodes relay the unicast frame, $r_{TU}$ for each node are different for their relative position in the topology. Also, $r_{RB}$ is different among nodes, depending on the node density within their communication range.

The active ratios of nodes are depicted in Fig. 6. The dotted lines are individual ratios of all the nodes in the network. The thick line with 'o' denotes the maximum active ratio at each wakeup interval. Another thick line with 'x' is the average value of the active ratios over all the nodes. From (15), the average active ratio attains the minimum value when the wakeup interval is 1.03 s. In the meantime, the maximum active ratio attains the minimum value when the wakeup

[8] Note that nodes are redistributed if the network topology is partitioned.

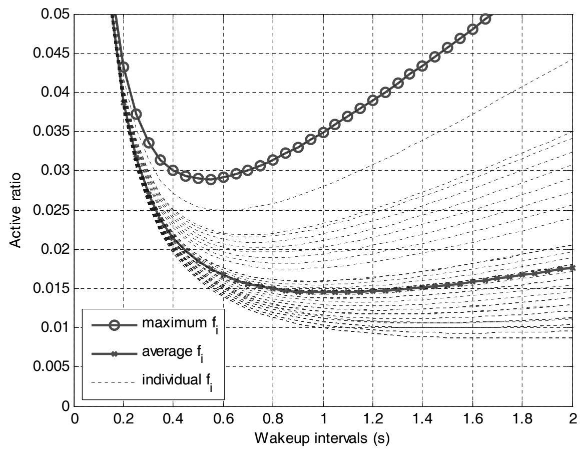


Fig. 6. Comparison of active ratios with the topology presented in Fig. 5.

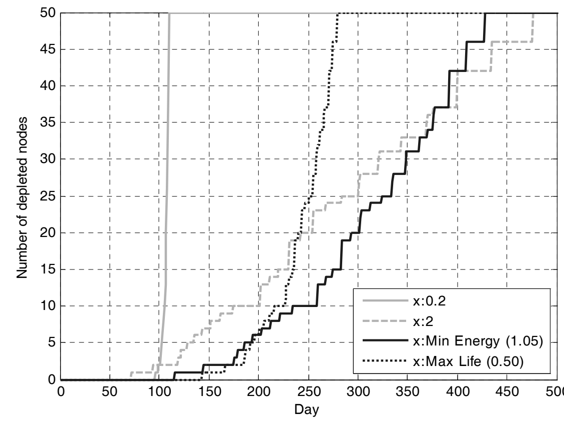


Fig. 7. Number of depleted nodes with homogeneous wakeup intervals.

interval is 0.52 s.

We investigate the battery depletion time of each node. Here, in order to calculate the network lifetime, we adopt $C_{battery} = 2000$ and $E[I_c] = 20$ in (2). We also assume that an exhausted battery is replaced with a new one without any delay for the case of minimum energy consumption. In case of the maximum network life time, we assume that the battery is not replaced once it is depleted.

The numbers of depleted nodes are presented in Fig. 7, where we compare four different values. First, when the wakeup interval is 0.2 s, the first node dies around the 94th day. Also, all the nodes require battery change within 110th day. In this case, due to the high energy consumption caused by frequent wakeup, all the nodes consume relatively high energy regardless of traffic load. When the wakeup interval increases to 2 s, the first node dies very quickly (72th day) while a node with the lowest traffic load enjoys the longest lifetime (475 days). Now, we apply the optimal values obtained from the analysis in the previous section. Since we use 0.05 s as the time unit, the wakeup interval that maximizes the network lifetime is calculated as 1.05 s (displayed as 'Min Energy (1.05)' in Fig. 7). With this value, 50 % of nodes survive until the 323th day. The case when the wakeup interval is 0.50 s (displayed as 'Max Life (0.50)' in Fig. 7) corresponds to the value for maximizing the network partition time. In this case, nodes spend more energy than those with 1.05 s and 2 s. However, the network partition time is increased to 142 days. For a more comprehensive study, we give results for a total of ten randomly generated topologies. Table II shows the network partition time of the topologies including the one presented in Fig. 5. Thus, we can conclude from our numerical results that we can efficiently control the network lifetime by tuning the wakeup interval.

### *B. Performance of global optimization with heterogeneous wakeup intervals*

In order to show the performance of global optimization, we adopt the same topology and traffic used in the previous subsection. In addition, the SP frame format is appended by two bytes in order to exchange values for the wakeup interval and the active ratio in MWB. In a similar manner, one additional byte is added in ELB in order to announce the remaining time. Consequently, the minimum active duration of MWB and ELB increases to 7.52 ms and 7.584 ms, respectively. To find the optimal values, we rely on a heuristic search. Although exhaustive search guarantees the optimality, the search space with 50 nodes and 40 steps of wakeup intervals (2 s/50 ms) is quite formidable. Thus, as a heuristic way for finding the optimum to minimize energy consumption, we iteratively adjust the wakeup interval of each node by 50 ms to decrease the overall energy consumption starting from the maximum value of 2 s. In order to maximize the network lifetime, we iteratively search for the most energy-consuming node in the network and adjust the wakeup intervals of its ancestors.

The number of depleted nodes in MWB are presented in Fig. 8. When all the nodes are forced to have a wakeup interval of 0.2 s, every node is depleted very quickly. Compared with the line of 0.2 s in Fig. 7, the lifetime of nodes become even shorter. The difference is mainly due to the overhead of using $t_{WI,MAX}$ for broadcasting. The effect of slightly increased active duration can be compared with the line of 2.0 s. In Fig. 7 and Fig. 8, the lines of 2.0 s have same conditions except the minimum active duration. Hence, those two lines behave in a very similar manner. However, note that the optimal result of MWB to maximize the network lifetime increases the lifetime to 159 days while the optimal result of MWB to minimize network-wide energy consumption is worse than that of the homogeneous wakeup interval. The poor performance of MWB for minimizing network-wide energy consumption mainly comes from the broadcasting rate. The performance of ELB nodes are compared with MWB in Fig. 9. In all cases, ELB increases the lifetimes of nodes. In particular, the network-partitioning time is given as 187 days, which indicates that ELB can increase the network lifetime more than 30 % with the same broadcasting rate compared to MWB. The benefit of ELB over MWB is expected to increase as the traffic load is more unbalanced over the network.

TABLE II
COMPARISON OF NETWORK LIFETIMES UNDER 10 DIFFERENT RANDOMLY-GENERATED TOPOLOGIES.

| Wakeup Interval (s) | Life Time (days) Scenario Number 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Global Homo: 0.2 | 94 | 92 | 88 | 92 | 97 | 88 | 92 | 97 | 93 | 88 |
| Global Homo: 2.0 | 72 | 57 | 45 | 55 | 75 | 45 | 55 | 75 | 58 | 45 |
| Global Homo: Min Energy | 116 | 102 | 86 | 98 | 127 | 86 | 98 | 127 | 103 | 88 |
| Global Homo: Max Life | 142 | 127 | 112 | 124 | 147 | 112 | 124 | 147 | 128 | 111 |
| Global ELB: Min Energy | 157 | 126 | 108 | 125 | 150 | 108 | 125 | 150 | 135 | 107 |
| Global ELB: Max Life | 187 | 146 | 130 | 141 | 162 | 130 | 141 | 162 | 160 | 149 |
| Heu ELB : Min Energy | 146 | 120 | 101 | 121 | 143 | 101 | 121 | 143 | 121 | 104 |
| Heu ELB : Max Life | 169 | 145 | 125 | 129 | 146 | 125 | 129 | 146 | 146 | 130 |

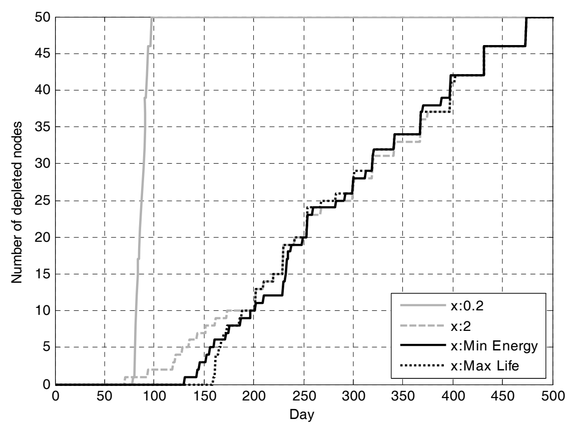


Fig. 8. Number of depleted nodes with heterogeneous wakeup intervals when MWB is adopted.

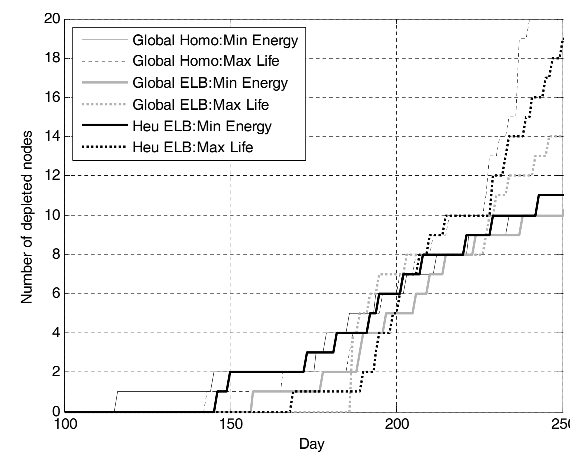


Fig. 10. Comparison of numbers of depleted nodes with localized algorithms.

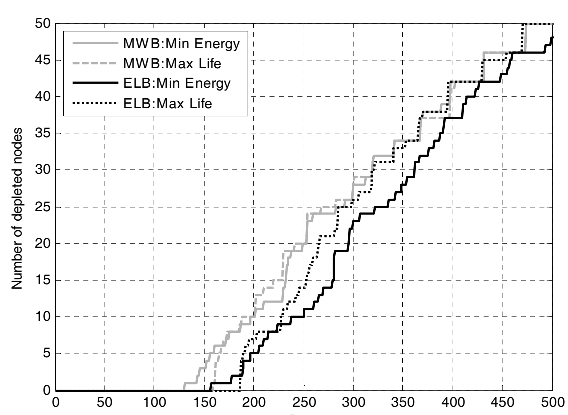


Fig. 9. Comparison of numbers of depleted nodes between two broadcast methods: Maximum Wakeup interval Broadcasting (MWB) and Efficient Local maximum Broadcasting (ELB).

### *C. Performance of local heuristic optimization with heterogeneous wakeup intervals*

We use the same environment used in the previous subsection to show the performance of the heuristic algorithms. The wakeup interval of every node is initially set to 2 s. Then, $h_i$ is calculated by setting $\delta = -0.05$ s, e.g., reducing the wakeup interval by 0.05 s. At each node $i$, if $h_i(-0.05)$ is less than zero, $x_i$ is updated to $x_i - 0.05$. Else, if $h_i(0.05)$ is smaller than zero, then $x_i$ is updated to $x_i + 0.05$. Otherwise, we keep the same wakeup interval. In this manner, the algorithm iteratively finds a solution.

The results for ELB are given in Fig. 10. In the case of the network partition time, the heuristic approach gives the lifetime of 169 days. Due to the local information exchange, this value is shorter than that of the global optimal solution (187 days). Still, the localized approach gives quite a longer lifetime than the best one with the homogeneous wakeup interval (142 days). Further results are given in Table II. By comparing the network lifetimes in Table II, it can be shown that the proposed localized algorithms give competitive performance.

## VII. CONCLUSION

In this paper, we have proposed a framework for optimizing the energy consumption of WSNs that adopt an asynchronous wakeup schedule. The contribution of this paper can be summarized as follows. First, in order to show the effect of the wakeup interval, we proposed and empirically validated an analytical energy consumption model. Second, with the proposed model, we showed that two optimization problems, to minimize network energy consumption and to maximize network lifetime, are convex. We numerically verified the performance of the proposed framework and showed that it successfully fulfills our design objectives. Third, in order to further enhance network performance, two broadcasting algorithms, entitled Maximum Wakeup interval Broadcast (MWB) and Efficient local maximum Broadcast (ELB), were proposed. These broadcasting algorithms allow each node to have a different wakeup interval. We showed that the global solution with ELB performs the best among all the proposed algorithms. Last, in order to reduce overhead for global optimization, we proposed two localized optimization algorithms, which shows promising performance.

## APPENDIX
## CALCULATION OF THE OVERLAPPED TIME

In order to derive the average overlapped time, we use the start time of the periodic active duration as a reference time. Thus, if any activity (either transmission or reception) of the node starts at the beginning of the active duration, the starting time is zero. The time linearly increases until it reaches to $t_{WI}$. Then, the value is reset to zero again. With this reference time, the average overlapped time $E[t_{OTU}]$ for unicast transmission is derived from three time durations. If the start time $t$ of the activity is between 0 and $t_{MinAD}$, the transmission time and the active duration are overlapped by an amount of $t_{MinAD}-t$. If $t$ is between $t_{WI} - (t_{ON} + E[t_{PU}] + E[t_U])$ and $t_{WI} - (t_{ON} + E[t_{PU}] + E[t_U] - t_{MinAD})$, the overlapped time is $t - \{t_{WI} - (t_{ON} + E[t_{PU}] + E[t_U])\}$. If $t$ is between $t_{WI} - (t_{ON} + E[t_{PU}] + E[t_U] - t_{MinAD})$ and $t_{WI}$, the overlapped time is $t_{MinAD}$. Hence, we have

$$t_{WI} E[t_{OTU}] = \int_0^{t_{MinAD}} (t_{MinAD} - t)dt + \int_0^{t_{MinAD}} t dt + \int_0^{t_{ON}+E[t_{PU}]+E[t_U]-t_{MinAD}} t_{MinAD} dt.$$

Consequently, $E[t_{OTU}]$ becomes

$$E[t_{OTU}] = \frac{(t_{ON} + E[t_{PU}] + E[t_U])t_{MinAD}}{t_{WI}}. \quad (24)$$

The average overlapped time $E[t_{ORU}]$ for unicast reception is defined only when an SP is received within the active duration. Therefore, if an SP frame is transmitted between $t_{ON}$ and $t_{MinAD} - t_{SP}$, the active duration is overlapped with the reception activity as $t_{MinAD} - t_{ON} - t$. Thus, $E[t_{ORU}]$ is derived as

$$E[t_{ORU}] = \int_0^{t_{MinAD}-t_{ON}-t_{SP}} (t_{MinAD} - t_{ON} - t)dt = \frac{(t_{MinAD} - t_{ON})^2 - t_{SP}^2}{2}.$$

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