Performance analysis and tuning of coexisting duty cycling WiFi and wireless sensor networks

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***Abstract*—Energy efficiency is of utmost importance for wireless networks due to the prevalent usage of mobile devices in WLAN and wireless sensor networks (WSNs). Consequently, duty cycling MAC protocols are widely employed in both WLAN (i.e., power saving mode - PSM) and WSNs (i.e., low power listening - LPL)). In a coexisting PSM and LPL network, a significant energy efficiency degradation has been observed because of large deviations of MAC protocol parameters from optimal values. To investigate these inefficiencies, analytical models are greatly preferred, when compared to simulation based methods, since they are faster, more scalable and can be used in optimization problems. Thus, this paper presents the first model for throughput and energy consumption analysis of coexisting PSM and LPL. Moreover, this paper presents a performance tuning method that minimizes the total energy consumption while satisfying the throughput requirements. Through extensive simulations, we demonstrate the accuracy of our proposed models and analysis. Finally, the proposed tuning method is evaluated, proving its effectiveness.**

I. Introduction

During the last decade, WiFi has become the most successful standard for wireless LAN because it provisions high speed access and because it is based on a distributed MAC protocol (i.e. IEEE 802.11). Currently, nearly all consumer electronic devices, such as smartphones, tablets and laptops etc., are WiFi enabled. Since duty cycling (i.e. making the device sleep as much as possible) is the supremely efficient strategy to save energy, 802.11 PSM, the default duty cycling MAC protocol for WiFi, is widely used in mobile devices. Moreover, it is expected that the fast growing market of WiFi industry will significantly expand with the popularization of Ad-Hoc networks (e.g., WiFi-Direct). Thus, the Ad-Hoc PSM, i.e., IBSS PSM, is becoming more and more important, and is one focus of this paper.

Recent years have also witnessed the thriving of WSN technology for applications such as building automation and environmental sensing, among others. The most widely deployed standard for WSNs is ZigBee, which uses IEEE 802.15.4 protocol as the default MAC. Similar to WiFi, ZigBee devices impose an even more stringent requirement for energy efficiency, due to the demand for them to work for months or years without battery charging/replacement. Thus a duty cycling mechanism is of paramount importance for WSNs. Additionally, a typical WSN consists of hundreds of ZigBee devices and a synchronous duty cycling MAC protocol is too expensive in terms of overhead. Therefore the asynchronous manner protocols such as LPL (a family of protocols) is preferred, which is our second focus.

The physical coexistence of WLAN and WSN is pervasive due to their extensive deployments. More importantly, since they both work on 2.4GHz (the most recent 5GHz/60GHz WiFi is for supplement of 2.4Ghz rather than replacement), their impact on each other's communication is inevitable. Specifically, due to the big difference between their underlying MAC protocols, the default protocol settings are usually not optimal for coexistence environment. Thus, the performances of both types are excessively impaired. For example, [1] [2] have demonstrated significant degradation of throughput for both 802.11 and 802.15.4 devices. Recently [3] proposed the first analytical model for single-cell coexistence of saturated 802.11 and 802.15.4 nodes, and [4] further extends the model to the unsaturated case. These models enable the performance optimization for the coexistence of non-duty-cycling MAC protocols, however, duty cycling case (e.g. PSM and LPL) is yet to be explored. As will be shown in section VII, the default duty cycling settings incur 13% energy waste, which motivates the urgent needs for accurate analytical models and efficient performance tuning methods.

In this paper, we propose the first analytical model for the coexistence of PSM and LPL devices. Due to the extremely high complexity of the duty cycling protocols, a Markov chain (MC) based model becomes intractable, the proposed model employs a divide-and-conquer strategy. Specifically, we first decompose the original problem twice, to investigate smaller problems which are solvable by the classical 2-D MC [5]; then by composing the solutions, together with a $M/G/1$ queueing analysis, we obtain an approximation of the original problem. This model is extensively validated by a ns-3 based simulator that is also presented in this paper. With the model, the expressions of two performance metrics, i.e. throughput and energy consumption are derived, which are then used in a tuning method that minimizes the total energy consumption of the network while satisfying the throughput constraints. We demonstrate that with the optimal duty cycling settings obtained from the tuning method, 13% more energy can be saved, proving its effectiveness. Our model can serve as a valuable stepping stone to study the more complex state of art duty cycling protocols.

The contributions of this paper are as follows: 1) it proposes the first analytical model for coexisting duty cycling networks; 2) it presents the closed form expressions for throughput and energy consumption; 3) it presents a performance tuning method which minimizes the total energy cost while meeting throughput constraints; 4) it presents the first ns-3 based coexistence simulator for duty cycling network; and 5) it validates the accuracy of the model, and evaluates the tuning method.

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II. State of the Art

Pioneering the analysis of network using Markov chain (MC), Bianchi [5] proposes an accurate 2-D MC model for saturated 802.11 network. Subsequently, research [6] [7] further improved its accuracy by adding retransmission limits and backoff counter freezing probability, among others. Since the saturated traffic assumption limits the practicability, various works [8] [9] extended the original model to unsaturated scenarios. Moreover, MC is also used to model different protocols such as 802.15.4 [10] [11], etc.

There have been approaches proposed to mitigate the performance degradation in coexisting 802.11 and 802.15.4 networks. One straightforward approach is based on frequency division [12] [13], which, however, is rendered ineffective in dense deployments. Other approaches exploit WiFi and WSN signal properties in asymmetric coexistence scenario (where ZigBee can sense WiFi, but not vice versa due to power level asymmetry) [14] [15] [16], which, although show promising results, are not applicable to symmetric case (i.e. every node can sense each other). [3] and [4] address the problem of symmetric coexistence by modeling 802.11 and 802.15.4 as two 2-D Markov chains.

More recently, researchers have attempted to analyze the networks with duty cycling devices. Zheng et al. [17] try to model the IBSS 802.11 PSM protocol, where a transient analysis is used. However, it relies on an unrealistic assumption of the MAC service time being either exponential or deterministic. While [18] models the 802.11 IBSS PSM as a pure 3-D Markov chain, where the key probability of a node being reset in a cycle is obtained by simulation, which makes this model futile. Rather than using a 3-D MC, Zhang et al. [19] utilizes an even more complex 4-D MC to study the same, which demonstrates very accurate results. Nevertheless, this model is too costly to solve due to the huge number of states involved. Instead of 802.11 PSM, [20] tries to utilize Markov chain to model X-MAC, which is a famous duty cycling protocol for WSN. However, it ignores the underlying CSMA/CA mechanism for medium access, which affects its practicability.

This paper studies the coexistence of two duty cycling protocols, namely 802.11 IBSS PSM and LPL. To tackle the high complexity of the problem, we decompose it into several smaller ones that are solvable through classical 2-D Markov chain. Then by composing these MC models and utilizing $M/G/1$ queueing theory, we solve the model and derive throughput and energy consumption expressions. Next we propose a tuning method that minimize total energy cost. Lastly, we validate the accuracy of the proposed model through extensive simulations, and evaluate the effectiveness of the tuning method.

III. Approximation Model

In this section, we first briefly introduce the network assumptions, the Ad-hoc 802.11 PSM and the LPL protocols. Then we describe the methodology used in the analysis. Finally an approximation based analytical model is thoroughly discussed in III-C, III-D and III-E.

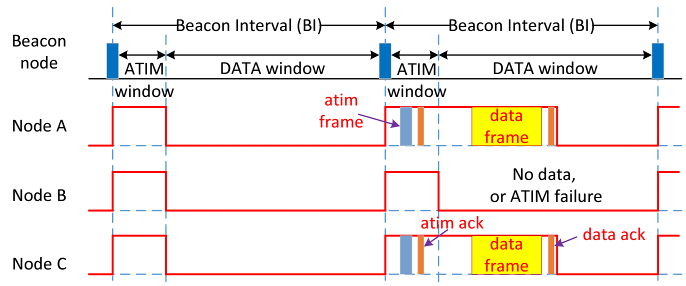

Fig. 1: 802.11 IBSS PSM Protocol

A. Preliminaries

1) Fundamental assumptions: We have made the following fundamental assumptions for simplicity: a) All devices are within a single wireless cell (i.e. symmetric), and each transmitter has one dedicated receiver (which is named "PSM pair" for short), i.e., there are $2W$ PSM nodes and $2B$ LPL nodes in total; b) The same type of devices are identical (i.e., same Poisson traffic pattern, same data packet size); c) The channel is ideal, implying communication failures are only due to collisions.

2) 802.11 PSM protocol: The Ad-Hoc PSM (namely IBSS) is defined in IEEE 802.11 standard [21]. Similar to infrastructural WiFi network, all devices in IBSS PSM are time synchronized with a centralized beacon node. As shown in Figure 1, each cycle is called a Beacon Interval (BI), and each BI has two fixed length windows, i.e. Announcement Traffic Indication Message (ATIM) window and DATA window. Every node wakes up at the beginning of a cycle, and after hearing a beacon, it stays awake for ATIM long to listen to or transmit an ATIM packet. The ATIM packet is a control frame exchanged by devices to determine the behavior in the following DATA window. Specifically, when a device has data for a receiver, it transmits an ATIM packet to the receiver during ATIM using the 802.11 DCF mechanism (i.e., random backoff). In response to an ATIM packet, the receiver will reply an ATIM-ACK. After a successful ATIM handshake, both devices will be in power-on mode in the following DATA window, where the actual packet transmission takes place. If a device fails to send an ATIM frame within the ATIM window, the data frame is buffered and another attempt will be made during the next BI cycle. A device enters the power save mode at the end of the ATIM window if it has no data to transmit/receive, or the transmission/reception in ATIM window has failed. *To make the modeling tractable, we assume that a transmitter which succeeds in ATIM window can only send one packet in the following DATA window.*

3) LPL protocol: LPL is considered in this paper because it is the most widely used duty cycling protocol for WSNs. Figure 2 demonstrates how LPL works. Specifically, a receiver (e.g., node B or C here) wakes up periodically to check if there is a data for it, and the duty cycle ratio determines its awake duration in each cycle. Regardless of whether the reception is successful or not, the receiver immediately goes back to sleep whenever its awake time is exhausted. While for a sender (e.g., node A), it wakes up right away if a packet needs to be transmitted, and then it repeatedly sends the packet

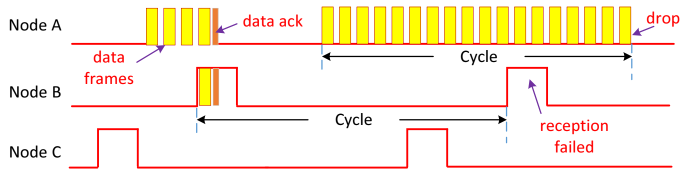

Fig. 2: LPL Protocol

(according to the 802.15.4 protocol, i.e., it backs off first, then checks channel (namely the clear channel assessment (CCA)) and sends data only if the channel is idle) and wait for the reply from the corresponding receiver, until it succeeds or the entire cycle is used up. Since a receiver has the same cycle length as the sender, it always has a chance to receive that packet. If the transmission succeeds, the sender goes to sleep when it receives the reply; otherwise the packet is dropped after it is retried for one cycle.

B. Methodology

1) Challenges: Analyzing the performance of coexisting 802.11 PSM and LPL devices is very challenging owing to:

First, in PSM, the number of active nodes (i.e., the nodes having data to send) in the network decreases in the ATIM window and DATA window because a node can only send one notification and one data packet, respectively. Thus, the classical method which is based on a 2-D Markov chain is infeasible for PSM because it assumes that the number of active nodes is constant (i.e., saturation). Moreover, since the ATIM window and DATA window are finite, it is possible that a node gets reset (i.e. the ongoing transmission (if any) is aborted; the contention window and backoff stage are reset to their initial values) before it succeeds, thus within a transmission cycle, PSM cannot actually reach the stationary state (i.e., it is not independent of time). Therefore, in order to model PSM as a MC, two extra dimensions are needed, one for the number of current active nodes and the other for the residual time in the ATIM/DATA window [19]. Since the time factor becomes one dimension in the MC, the Markov property is still maintained. This method gives high accuracy, however, it becomes intractable very easily due to the immense number of states derived from the large size of the DATA window (100ms/10μs=10000, where 10μs is the length of a timeslot).

Second, since LPL is asynchronous, it is even more complicated than the synchronous PSM. Similar to PSM, due to the duty cycling property, an LPL node may be reset (same as for PSM) when its cycle is exhausted, thus a dimension for the residual time of a cycle is necessary for a Markov chain based model. Nevertheless, to save energy the most, LPL usually has a very long cycle (e.g. 500ms) which simply renders the MC based method infeasible.

2) Main idea: To overcome the intractability of the high dimensional Markov chain, this paper employs an approximation approach which is simple, computationally efficient and reasonably accurate.

Step 1: As we know, the seminal 2-D Markov chain model is for the saturation scenario which is easier to study due to the independence of the the number of active nodes. Thus our main idea is to decompose the original problem of modeling the coexistence of PSM and LPL nodes with unsaturated traffic into several smaller yet tractable ones, i.e., the modelings of the coexistence of different numbers of saturated PSM and LPL nodes [7]. Then, if the distribution of the number of saturated nodes (i.e. $Pr(n_W{=}w, n_B{=}b), w{\in}[0, W], b{\in}[0, B]$ where W and B are the number of PSM and LPL transmitters, respectively) can be obtained, the saturation models can be applied to approximate the unsaturated network effortlessly. These ideas are illustrated as the "1^{st} Decompos." and the "2^{nd} Compos." in Figure 3. The model for the saturated coexistence is discussed in III-D, and the 2^{nd} composition is in III-E.

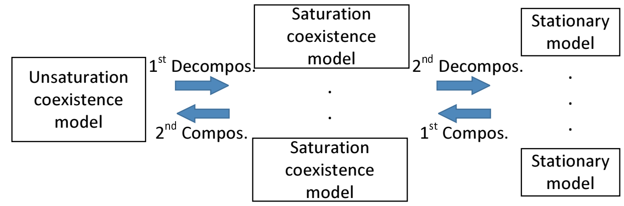

Fig. 3: Main idea illustration

Step 2: However, the saturation problem itself is still very challenging due to the aforementioned "reset" mechanism, thus it is necessary to be further decomposed (i.e. "2^{nd} Decompos." in Figure 3). Basically, because of the "reset", a PSM or an LPL node cannot become stationary in a cycle. We notice, however, that the length of a cycle is several orders of magnitude greater than a transmission (because an active node can only send one packet). In other words, although the stationary state cannot be reached, the saturation 2-D MC models for 802.11 and 802.15.4 (named *stationary model* here) should yield reasonably good approximation (i.e. "1^{st} Compos."). Specifically, when modeling the self-behavior of a node, the "reset" probability is ignored and the classical 2-D MC model is used (but notice that such "reset" probability takes effect (i.e. exists) for all other cases). The stationary models are described in detail in Section III-C.

3) Key Assumptions: Some key assumptions are made for the modeling: a) The "independent and constant" assumption for transmission attempt probability τ and the conditional collision probability p is applied as in [5]; b) Given w active PSM and b active LPL nodes, the corresponding reset probability (see $Pe_{W_{w,b}}$ and $Pe_{B_{w,b}}$ in Section III-C4 and III-C5, respectively) are independent and are constant for same type of devices.

C. Stationary Model

There are three stationary models that we consider for PSM, LPL and the channel, respectively, where PSM and LPL ones describe the self-behaviors of each, while the channel model analyzes their interactions. We assume that for each model, there are w ($w{\in}[0, W]$) and b ($b{\in}[0, B]$) active PSM and LPL nodes, respectively. *Note that this info. is denoted by the subscript w, b in the following context.*

1) PSM Model: Let us denote by $\tau_{W_{w,b}}$ the probability that a PSM node attempts to send, and $p_{W_{w,b}}$ the conditional collision probability. Then by the 2-D Markov chain model [5] for saturation 802.11 network, we have

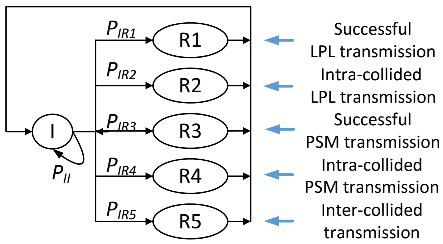

Fig. 4: Markov chain for the channel model

$$\tau_{W_{w,b}}=\frac{2(1-2p_{W_{w,b}})}{(1-2p_{W_{w,b}})(CW_0+1)+p_{W_{w,b}}\cdot CW_0\cdot(1-(2p_{W_{w,b}})^m)} \quad (1)$$

where CW_0 is the minimum contention window size and m is the maximum backoff stage.

2) LPL Model: Similar to the stationary model for PSM, we denote by $\tau_{B_{w,b}}$ the probability that an LPL node attempts to sense the channel, and $P_{I_{w,b}}$ the probability of the channel being idle, then by same approach as the 802.11 Markov chain model [5], we have the expression for $\tau_{B_{w,b}}$:

$$\tau_{B_{w,b}}=\frac{2}{3(P_{I_{w,b}}(CW_0'+1)+(1-P_{I_{w,b}})(CW_1'+1))} \quad (2)$$

where CW_0' and CW_1' are the contention window sizes for the two backoff stages of 802.15.4. Since $P_{I_{w,b}}$ represents the state of the channel, it will be derived in next section.

3) Model for the channel: The channel model is Markov chain based, which describes the state of the channel. As shown in Figure 4, I stands for the idleness of the channel and the R's represent different types of transmissions. Specifically, $R1$ and $R3$ represents a successful transmission of any LPL node and any PSM node, respectively; while $R2$ and $R4$ represents an intra-collision between LPL nodes only and between PSM nodes only, respectively; $R5$ denotes an inter-collision between LPL nodes and PSM nodes.

Let us first define a shorthand $SH_{B_{w,b}}$ for the probability that an LPL node stays silent, i.e. it either gets reset (w.p. $Pe_{B_{w,b}}$) or it is still backing off (w.p. $(1-Pe_{B_{w,b}})(1-\tau_{B_{w,b}})$), thus $SH_{B_{w,b}}\triangleq Pe_{B_{w,b}}+(1-Pe_{B_{w,b}})(1-\tau_{B_{w,b}})$. We also use the shorthand $SH_{W_{w,b}}$ for the probability that all PSM nodes keep silent, i.e. $SH_{W_{w,b}}\triangleq Pe_W+(1-Pe_W)(1-\tau_{W_{w,b}})^w$. Then the transition probabilities for the channel Markov chain can be derived as,

$$P_{IR1_{w,b}}=\left(b\cdot\tau_{B_{w,b}}\cdot(1-Pe_{B_{w,b}})\cdot SH_{B_{w,b}}^{b-1}\right)\cdot SH_{W_{w,b}}$$
$$P_{IR2_{w,b}}=\left(\sum_{i=2}^{b}\binom{b}{i}\tau_{B_{w,b}}^{i}(1-Pe_{B_{w,b}})^{i}\cdot SH_{B_{w,b}}^{b-i}\right)\cdot SH_{W_{w,b}}$$
$$P_{IR3_{w,b}}=\left((1-Pe_W)\cdot w\cdot\tau_{W_{w,b}}(1-\tau_{W_{w,b}})^{w-1}\right)\cdot SH_{B_{w,b}}^{b}$$
$$P_{IR4_{w,b}}=\left((1-Pe_W)\sum_{i=2}^{w}\binom{w}{i}\tau_{W_{w,b}}^{i}(1-\tau_{W_{w,b}})^{w-i}\right)\cdot SH_{B_{w,b}}^{b}$$
$$P_{IR5_{w,b}}=\left(1-SH_{B_{w,b}}^{b}\right)\cdot(1-Pe_W)\cdot(1-(1-\tau_{W_{w,b}})^{w})$$
$$P_{II_{w,b}}=1-\sum_{k=1}^{5}P_{IRk}$$
$$P_{I_{w,b}}=\frac{1}{1+\sum_{k=1}^{5}L_{R_k}P_{IRk_{w,b}}} \quad (3)$$

where $P_{I_{w,b}}$ represents the stationary probability for the channel being idle, which can be obtained by solving this Markov chain; L_{R_k} is the length of state $Rk, 1\leq k\leq 5$; $P_{IR1_{w,b}}$ is the transition probability from I to $R1$, i.e., only one LPL node attempts to transmit (w.p. $b\cdot\tau_{B_{w,b}}\cdot(1-Pe_{B_{w,b}})\cdot SH_{B_{w,b}}^{b-1}$) and all PSM nodes do not send (w.p. $SH_{W_{w,b}}$); other transition probabilities are similar to $P_{IR1_{w,b}}$, which are ignored here for brevity and space limit.

Based on how the conditional collision probability for PSM (i.e. $p_{W_{w,b}}$) is defined, we can also derive $p_{W_{w,b}}$ by using $SH_{B_{w,b}}$ from the channel model, as:

$$p_{W_{w,b}}=1-(1-\tau_{W_{w,b}})^{w-1}\cdot SH_{B_{w,b}}^{b} \quad (4)$$

So far we have four expressions (1)-(4) with six unknowns $\tau_{W_{w,b}}$, $\tau_{B_{w,b}}$, $P_{I_{w,b}}$, $Pe_{B_{w,b}}$, $Pe_{W_{w,b}}$ and $p_{W_{w,b}}$. Thus, two more equations are necessary for this system to be solvable. Now we begin to discuss how to derive $Pe_{W_{w,b}}$ and $Pe_{B_{w,b}}$.

4) $Pe_{W_{w,b}}$: According to the definition of $Pe_{W_{w,b}}$, since all PSM nodes are synchronized with each other, the probability of a PSM node to be be reset is simply the probability that a window is exhausted. Therefore for ATIM and DATA window, we have two different values for it, which are:

$$Pe_{W_{w,b}}\triangleq Pe_W=\frac{1}{T_{W_A}}\text{ (for ATIM) or }\frac{1}{T_{W_D}}\text{ (for DATA)} \quad (5)$$

where T_{W_A} and T_{W_D} are the lengths of the ATIM and DATA window, respectively.

5) $Pe_{B_{w,b}}$: For $Pe_{B_{w,b}}$, since whether or not an LPL node gets reset depends on if the corresponding receiver receives successfully, thus the reset probability is actually the probability that a node fails to transmit within the awake period of its receiver. Let us denote by T_B the cycle length of LPL, and by Pa the ratio of a receiver being awake in a cycle. Thus the awake time of a receiver is $Ta_B=T_B\cdot Pa$. Given that the receiver is awake, there are three possible statuses for a transmitter: i) mute (due to backing off or busy channel); ii) failed transmission; and iii) successful transmission, respectively. The probabilities for a node to enter one of these three statuses are as follows:

$$Pi_{B_{w,b}}=1-P_{I_{w,b}}\cdot\tau_{B_{w,b}}$$
$$Pf_{B_{w,b}}=P_{I_{w,b}}\cdot\tau_{B_{w,b}}\left(1-SH_{B_{w,b}}^{b-1}\cdot SH_{W_{w,b}}\right)$$
$$Ps_{B_{w,b}}=P_{I_{w,b}}\cdot\tau_{B_{w,b}}\cdot SH_{B_{w,b}}^{b-1}\cdot SH_{W_{w,b}}$$

The expressions are self-explanatory and the description is thus ignored for brevity.

To compute the probability that a node failed to send a packet within Ta_B of its receiver (i.e. $Pe_{B_{w,b}}$), we note that a sender succeeds only if there is a successful transmission before the end of Ta_B. Since a node can only be in one of the aforementioned three statuses at any given point of time, and if we name both the mute and failed transmission statuses as "waiting status", there must be zero or more waitings before a success. Thus we can use the Geometric distribution to derive the probability of the number of waitings (i.e. random variable X) before the first successful transmission as follows:

$$Pr(X=k)=(Pi_{B_{w,b}}+Pf_{B_{w,b}})^k Ps_{B_{w,b}}=(1-Ps_{B_{w,b}})^k Ps_{B_{w,b}}$$

where $1-Ps_{B_{w,b}}$ is the probability for a waiting status.

Thus $Pe_{B_{w,b}}$ is simply the corresponding CDF for r.v. X, which can be expressed as,

$$Pe_{B_{w,b}}=Pr(X\geq K)=(1-Ps_{B_{w,b}})^{K+1} \tag{6}$$

where K is the number of waitings a Ta_B can accommodate. The question now becomes how to compute K. Since we already have Ta_B, if we know the average time cost of each waiting $Du_{B_{w,b}}$, then K is simply $\frac{Ta_B-Ds_B}{Du_{B_{w,b}}}$, where Ds_B is the length of a successful transmission.

However, since a waiting can either be a mute (which lasts three timeslots) or a failed transmission (uses Df_B timeslots), we thus compute the length of a waiting as the average length of a mute and a failed transmission, i.e.,:

$$Du_{B_{w,b}}=\frac{Pf_{w,b}}{1-Ps_{B_{w,b}}}Df_B+\frac{Pi_{w,b}}{1-Ps_{B_{w,b}}}\cdot 3$$

Then K is obtained, and $Pe_{B_{w,b}}$ can be derived by using Equation (6). With (1)-(6), $\tau_{W_{w,b}}$, $\tau_{B_{w,b}}$, $P_{I_{w,b}}$, $Pe_{B_{w,b}}$, $Pe_{W_{w,b}}$ and $p_{W_{w,b}}$ can be obtained numerically. *It is worth emphasizing that the model here are only for a specific pair of w and b (which we name **(w,b)-stationary-model**), and $W\times B$ rounds of computations are needed to get all required values for the approximation approach to work.*

As we know, the stationary model is used in the 1^{st} composition process, i.e., approximating the saturation coexistence model, which is discussed in the next section.

D. Model of coexistence of saturated PSM and LPL

Since the objective is to derive the expressions of throughput and energy consumption for unsaturated duty-cycling coexistence problem, some higher level metrics rather than the fundamental probabilities obtained in the previous section are needed to achieve our goal more efficiently. The higher level metric we consider is the per-packet average MAC service time, which is the duration from the time a packet becomes the head of the queue until it gets transmitted successfully or dropped (for LPL only). As shown later, this metric is proved to be not only easy to obtain, but also convenient in deriving throughput and energy consumption. Therefore, the service time for PSM (denoted by $S_{W_{w,b}}$) and LPL (by $S_{B_{w,b}}$) are our focus in the following few subsections.

1) PSM: To obtain $S_{W_{w,b}}$, we need to know the probability that a packet gets transmitted successfully in a cycle (by $P_{W_{w,b}}$). Since each PSM cycle has ATIM and DATA windows, for a node to succeed in a cycle, it has to be successful in both windows. We denote by $P_{WA_{w,b}}$ and by $P_{WD_{w,b}}$ the probabilities that a packet gets transmitted successfully in ATIM and in DATA, respectively, and then we have $P_{W_{w,b}}=P_{WA_{w,b}}\cdot P_{WD_{w,b}}$. Due to the reset event, each cycle is independent from the one experienced before, thus $S_{W_{w,b}}$ can be derived by using the results of the Geometric distribution with respect to $P_{W_{w,b}}$ as:

$$S_{W_{w,b}}=T_W\cdot\sum_{i=0}^{\infty}(i+1)(1-P_{W_{w,b}})^i P_{W_{w,b}}=\frac{T_W}{P_{W_{w,b}}} \tag{7}$$

As for $P_{W_{w,b}}=P_{WA_{w,b}}\cdot P_{WD_{w,b}}$, in next sections we discuss how to obtain each for ATIM and DATA, respectively.

a) ATIM window: Here we notice that the probability $P_{WA_{w,b}}$ is actually the ratio of nodes that finish their transmissions in ATIM (i.e., $P_{WA_{w,b}}=\frac{\text{\# successful nodes in ATIM}}{w}$), thus the number of successful nodes for ATIM window is needed. Obviously, since the length of ATIM window is fixed, if the average time usage of each successful transmission is known, the number of successful nodes can be obtained by very trivial counting. Then the problem becomes how to compute the average length of each successful transmission.

As known, we assume the PSM and LPL nodes are saturated. Thus for PSM, at the beginning of each cycle (also the start point of the ATIM window), there are w active PSM and b active LPL nodes, implying that it can be approximated by the aforementioned (w,b)-stationary-model.

To compute the average length of the first successful transmission for the case (w,b) in ATIM (denoted by $s_{WA_{w,b}}$), we notice that before the first successful transmission, there are three possible cases, i.e., idle, LPL transmission or failed PSM transmission. Since the transition probability for each case can be easily obtained from the stationary channel model, we can first compute their average length and then utilize the Geometric distribution again to compute $s_{WA_{w,b}}$:

$$P_{IB_{w,b}}=P_{IR1_{w,b}}+P_{IR2_{w,b}}+P_{IR5_{w,b}}$$

$$P_{IWc_{w,b}}=P_{IR4_{w,b}}$$

$$Du_{w,b}=\frac{P_{II_{w,b}}\cdot 1+P_{IB_{w,b}}\cdot Ds_B+P_{IWc_{w,b}}\cdot Df_W}{P_{II_{w,b}}+P_{IB_{w,b}}+P_{IWc_{w,b}}}$$

$$P_{IWs_{w,b}}=P_{IR3_{w,b}}$$

$$s_{WA_{w,b}}=(1-P_{I_{w,b}})\cdot\frac{Ds_B}{2}+\frac{1-P_{IWs_{w,b}}}{P_{IWs_{w,b}}}\cdot Du_{w,b}+Ds_W$$

where $P_{IB_{w,b}}$ is the transition prob. from idle to an LPL transmission, $P_{IWc_{w,b}}$ is the one to a failed PSM transmission and $Du_{w,b}$ is the average length of the three cases. In the last equation, $((1-P_{I_{w,b}})\cdot\frac{Ds_B}{2})$ is the length of possible ongoing LPL transmissions at the beginning of the PSM cycle, $\frac{1-P_{IWs_{w,b}}}{P_{IWs_{w,b}}}$ is the number of failures (including the three cases) before the first success, which is obtained by Geo-Dist. Ds_W is the size of a successful PSM transmission.

Then after one PSM node succeeds, it quits the contention and thus the number of active PSM nodes decrements (i.e., becomes $w-1$), then the new status can be approximated by the $(w-1,b)$-stationary-model. This repeats until the ATIM window is used up. Since $s_{WA_{w,b}}$ is obtained, we can compute $s_{WA_{w-1,b}}, s_{WA_{w-2,b}}, \cdots, s_{WA_{1,b}}$ using a similar approach. Finally, the average number of packets transmitted successfully within T_{W_A} can be computed as follows:

$$\max_{\sum_{i=0}^{x_{w,b}} s_{WA_{w-i,b}}\leq T_{W_A}} \quad x_{w,b}\leq w$$

where $x_{b,w}$ is the average number of nodes that are successful in the ATIM window, thus $P_{WA_{w,b}}=\frac{x_{w,b}}{w}$.

b) DATA window: Inside DATA window, since the number of remaining active PSM is only $x_{w,b}$, there are at most $x_{w,b}+1$ values for $s_{WD_{j,b}}, j\in[0,x_{w,b}]$ (corresponds to $s_{WA_{j,b}}$). Assume there are $y_{w,b}$ nodes succeed in the DATA window, then $P_{WD_{w,b}}=\frac{y_{w,b}}{x_{w,b}}$. The details of the derivation for $P_{WD_{w,b}}$ and $s_{WD_{j,b}}$ are ignored for conciseness due to their high similarities with $P_{WA_{w,b}}$ and $s_{WA_{j,b}}$. *It is worth noting that since the length of DATA window is very long compared to the length of a successful transmission, almost all $x_{w,b}$ nodes succeed (i.e. $y_{w,b} \approx x_{w,b}$, thus $P_{WD_{w,b}} \approx 1$).*

With $P_{WA_{w,b}}$ and $P_{WD_{w,b}}$ (thus $P_{W_{w,b}}$), $S_{W_{w,b}}$ is obtained by Equation (7).

2) LPL: As described before, the number of active PSM nodes decreases in the ATIM/DATA window, which also affects the performance of LPL. Thus our idea to tackle this problem is still to utilize the stationary model, i.e., we first compute the MAC service time of LPL packets under different number of PSM nodes $j \in [0, w]$ by the (j, b)-stationary model as:

$$s_{B_{j,b}} = Pe_{B_{j,b}} \cdot T_B + (1 - Pe_{B_{j,b}}) \cdot \frac{T_B}{2}$$

where $\frac{T_B}{2}$ comes from the observation that when an LPL node succeeds in its cycle (w.p. $1 - Pe_{B_{j,b}}$), the average time cost is $\frac{T_B}{2}$ because the receiver, on average, wakes up in the middle of a cycle (i.e., uniform distribution).

Then the ratio (i.e. distribution) of j active PSM nodes within T_W (denoted by $\gamma_{W_{j,b}}$) can be obtained by the following equation,

$$\gamma_{W_{j,b}} = \frac{s_{WA_{j,b}} \cdot \mathbb{1}_{[w - x_{w,b}, w]}(j) + s_{WD_{j,b}} \cdot \mathbb{1}_{[x_{w,b} - y_{w,b}, x_{w,b}]}(j)}{T_W}$$

where $\mathbb{1}_{[range]}(j)$ is an indicator function (namely the function equals to 1 if $j \in [range]$, otherwise it is 0), $s_{WA_{j,b}}$ and $s_{WD_{j,b}}$ are described in the previous section.

Finally the actual MAC service time of an LPL packet under w saturated PSM and b saturated LPL $S_{B_{w,b}}$ is computed by taking the expectation of $s_{B_{j,b}}$ over the distribution of different active PSM nodes in T_W, i.e.,:

$$S_{B_{w,b}} = \sum_{j=0}^{w} \gamma_{W_{j,b}} \cdot s_{B_{j,b}} \qquad (8)$$

So far, the key metrics for w saturated PSM and b saturated LPL have been obtained in expressions (7) and (8), we are now ready to apply it to our objective, i.e., the unsaturated coexistence case.

E. Model of coexistence of unsaturated LPL and PSM

As mentioned in Section III-B2, the main idea is to obtain the distribution of the number of saturated PSM and LPL nodes from the traffic pattern, and then to approximate the unsaturated coexistence using the results from the analysis of saturated case. Since the per-packet average MAC service time is important in throughput and energy consumption derivation, we thus compute them for unsaturated PSM and LPL (denoted by S_W and S_B) through $S_{W_{w,b}}$ and $S_{B_{w,b}}$.

1) M/G/1 model: To compute the distribution of the number of saturated PSM and LPL nodes from the Poisson traffic pattern, we employ two M/G/1 queueing models, which are described below for PSM and LPL, respectively.

a) PSM: M/G/1 queueing theory is useful to derive the queue idle probability $Q0_W$ for PSM as:

$$Q0_W = 1 - \lambda_W \cdot S_W \qquad (9)$$

where λ_W is the data arrival rate and S_W is the per-PSM-packet average MAC service time for unsaturated case (derived later).

Then with $Q0_W$, the distribution of the number of saturated PSM nodes (denoted by β_{W_w} here, w represents # saturated PSM nodes) can be obtained through:

$$\beta_{W_w} = \binom{W}{w} (1 - Q0_W)^w \cdot Q0_W^{W-w}, w = 0, 1, \cdots, W \qquad (10)$$

b) LPL: Similar to the analysis for PSM, we have the following two expressions for LPL:

$$Q0_B = 1 - \lambda_B \cdot S_B \qquad (11)$$

$$\beta_{B_b} = \binom{B}{b} (1 - Q0_B)^b \cdot Q0_B^{B-b}, b = 0, 1, \cdots, B \qquad (12)$$

where λ_B, S_B and β_{B_b} have similar meanings as those for PSM above.

2) Per-packet average MAC service time: The last steps are deriving S_W and S_B. Since both the distributions for the number of saturated nodes (i.e. β_{W_w} and β_{B_b}) and the per-packet average MAC service times for saturated case (i.e. $S_{W_{w,b}}$ and $S_{B_{w,b}}$) are obtained, the 2^{nd} composition processes are straightforward, as follows:

$$S_W = \frac{\sum_{w=1}^{W} \beta_{W_w} \cdot \sum_{b=0}^{B} \beta_{B_b} \cdot S_{W_{w,b}}}{1 - \beta_{W_0}} \qquad (13)$$

$$S_B = \frac{\sum_{b=1}^{B} \beta_{B_b} \cdot \sum_{w=0}^{W} \beta_{W_w} \cdot S_{B_{w,b}}}{1 - \beta_{B_0}} \qquad (14)$$

By solving the equations (9)-(14), all unknowns are attained. Note that equation (10) (or (12)) represents $W+1$ (or $B+1$) equations, but since the number of unknowns and equations are the same, they are solvable.

IV. Performance analysis

With S_W, S_B and all other necessary metrics such as β_{W_w}, β_{B_b} etc, the expressions for throughput and energy consumption are derived in this section.

A. Throughput

An LPL sender simply drops a packet if it fails in the cycle, while PSM retries until the packet succeeds. Thus, expressions of their throughput is defined differently.

1) PSM: For PSM, the maximum throughput is simply the reciprocal of per-packet MAC service time. If current data arrival rate is less than the maximum throughput, namely the traffic is unsaturated, the actual throughput equals to λ_W, otherwise (i.e. the traffic becomes saturated) the actual throughput is the maximum. Thus the expression for the actual throughput of a PSM sender is:

$$Th_W = \lambda_W \cdot \mathbb{1}_{[0, \frac{1}{S_W})}(\lambda_W) + \frac{1}{S_W} \cdot \mathbb{1}_{[\frac{1}{S_W}, +\infty)}(\lambda_W) \qquad (15)$$

2) LPL: For LPL, the throughput is defined as the probability that a packet succeeds in a cycle, thus:

$$Th_B = \sum_{b=1}^{B} \beta_{B_b} \cdot \sum_{w=0}^{W} \beta_{W_w} \cdot (1 - F_{B_{w,b}}) \qquad (16)$$

where $F_{B_{w,b}}$ is the probability of an LPL packet being dropped (i.e. an LPL getting reset) in a cycle under saturated case, which can be obtained through $F_{B_{w,b}} = \sum_{j=0}^{w} \gamma_{W_{j,b}} \cdot Pe_{B_{j,b}}$, where $Pe_{B_{j,b}}$ is the probability that an LPL node gets reset in the **stationary model** (see equation (6)).

B. Energy consumption

The energy consumption is defined as the average percentage of time that a node stays awake within a cycle.

1) PSM: For PSM, there are three different cases, i.e., failure due to ATIM failure w.p. $1-P_{WA_{w,b}}$, failure due to DATA failure w.p. $P_{WA_{w,b}} \cdot (1-P_{WD_{w,b}})$, success w.p. $P_{W_{w,b}} = P_{WA_{w,b}} \cdot P_{WD_{w,b}}$. These cases correspond to different energy consumption, i.e., T_{W_A}, T_W and $L_{W_{w,b}}$, respectively, where L_W is the average energy consumption when a node successfully finishes its transmission in a cycle. Thus:

$$L_{W_{w,b}} = T_{W_A} + \frac{1}{y_{w,b}} \sum_{i=0}^{y_{w,b}} \sum_{j=0}^{i} s_{WD_{(y_{w,b}-j),b}}$$

where $y_{w,b}$ and $s_{WD_{k,b}}$ are defined in Section III-D1b.

Therefore the expression for energy consumption under the case (w, b) is:

$$En_{W_{w,b}} = \frac{T_{W_A}}{T_W} + \frac{(L_{W_{w,b}} - T_{W_A}) \cdot P_{WA_{w,b}}}{T_W \cdot (1-P_{WA_{w,b}})} \cdot \ln\left(\frac{1}{P_{WA_{w,b}}}\right)$$

Finally, since a PSM receiver consumes the same energy with its transmitter due to their synchronization, the overall energy consumption of a PSM pair is expressed as:

$$En_W = \sum_{w=1}^{W} \beta_{W_w} \cdot \sum_{b=0}^{B} \beta_{B_b} \cdot En_{W_{w,b}} \quad (17)$$

2) LPL: The expression for LPL is extremely simple because according to the LPL protocol, an LPL node stays awake whenever it has data in its queue, thus for a transmitter $En_{B_T} = 1 - Q0_B$. While for a receiver, En_{B_R} is simply the awake ratio Pa, i.e. $En_{B_R} = Pa$.

Thus the overall energy consumption of an LPL pair is:

$$En_B = \frac{(1 - Q0_B + Pa)}{2} \quad (18)$$

With Equations (15)-(18), performance can be optimized by formulating the requirement as an optimization problem with constraints, which is the focus of the following section.

V. Performance tuning

In this section, we discuss an offline tuning method, which can be used in the network design stage to obtain optimal values for key parameters like duty cycling settings, etc.

As we know, a network usually has a fairly stable long term traffic pattern, however, since the default configurations for the duty cycling parameters are not optimized for coexistence scenarios, some energy is excessively wasted. To tackle this problem, we utilize the proposed model to optimize these parameters such that the total energy consumption is minimized while the traffic requirement is still met. The corresponding optimization formulation is as follows:

$$\begin{aligned} \underset{R_W, R_B, T_W, T_B}{\text{minimize}} \quad & En \triangleq \frac{En_W \cdot W + En_B \cdot B}{W+B} \\ \text{subject to} \quad & Th_W == \lambda_W, \\ & Th_B > 85\%, \\ & R_W, R_B, T_W, T_B > 0. \end{aligned}$$

where En is the total energy consumption of both PSM and LPL (note that En is a percentage), R_W and R_W are the duty cycle ratios for PSM and LPL, respectively ($R_W = \frac{T_{W_A}}{T_W}$ and R_B is the LPL awake ratio Pa). The constraint $Th_W == \lambda_W$ means that all input traffic is guaranteed to be served by a PSM transmitter, while for an LPL sender, since LPL has no MAC layer retransmission mechanism, we ensure 85% of the traffic be successful (100% reliability can be achieved by WSN applications).

To solve this optimization problem, we notice that the solution space is not continuous because the unit of T_W and T_B is timeslot ($=10\mu s$), we thus employ the "pattern search" [22] which is a powerful numerical optimization method for non-continuous or non-differentiable problems. Specifically, we input the model to MATLAB and then formulate and solve the problems with the "patternserach toolbox". Usually, the convergence speed depends on the choices of the initial guesses, but the patternserach method always converges, which proves its effectiveness.

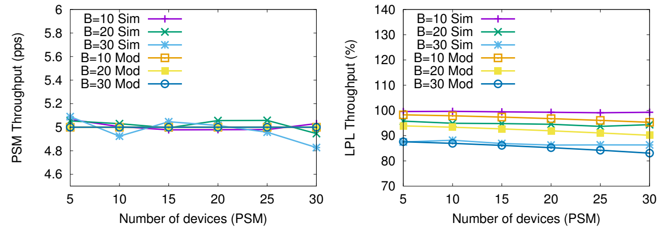

Fig. 5: Throughput of model and simulator vs # devices.

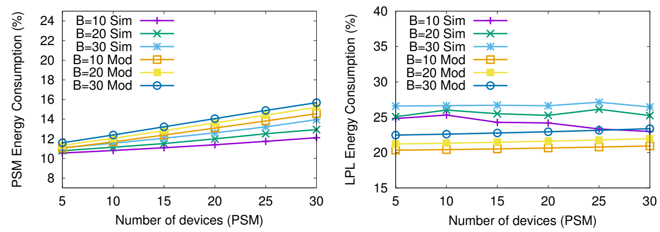

Fig. 6: Energy cost of model and simulator vs # devices.

VI. Model validation

To validate our model, a coexistence simulator for duty cycling network was implemented in the well-known ns-3 simulation framework. Specifically, we implemented in ns-3.25 the PSM protocol based on the WiFi module, the LPL protocol based on the LrWPAN module and also replaced their default channel modules with a common one such that PSM and LPL nodes were sensible to each other. Then all PSM and LPL nodes are placed in single cell to form a symmetric coexistence scenario, and we compare the throughput and energy consumption obtained from it against those from the proposed analytical model.

We performed extensive simulations by varying following parameters: number of senders W and B, the per-node offered load (packet arrival rate) λ_W and λ_B, and the duty cycling settings (i.e. lengths T_W and T_B, and ratios R_W and R_B). The default settings (typical for common smart-home devices) are: $W=20, CW_0=16$, $m=6$, $P_W=1000$ bytes, $\lambda_W=5p/s$, $T_W=100ms$, $R_W=10\%$ for PSM, and $B=20, CW'_0=120, CW'_1=70$, $P_B=30$ bytes, $\lambda_B=1p/s$, $T_B=400ms$, $R_B=5\%$ for LPL.

Typically, the time spent for solving the model is about two minutes on a fast PC (with Intel Core i7 4790K CPU, 16GB of RAM and 256GB SSD HD), while it takes around 20 minutes

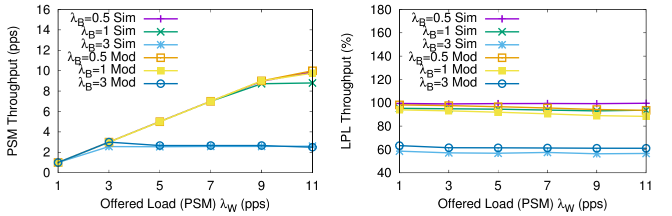

Fig. 7: Throughput of model and simulator vs offered load.

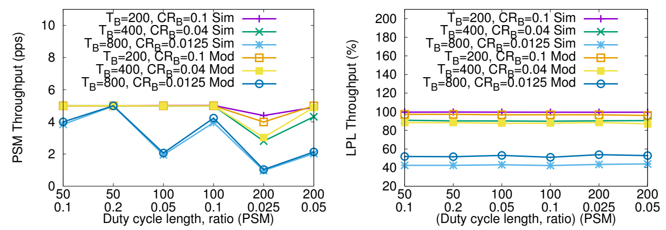

Fig. 9: Throughput of model and simulator vs duty cycle.

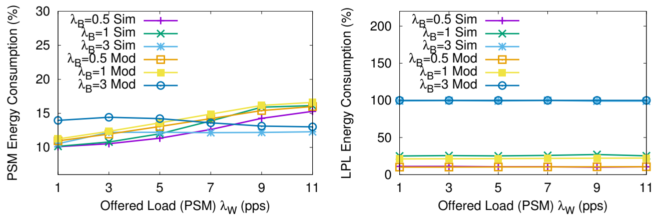

Fig. 8: Energy cost of model and simulator vs offered load.

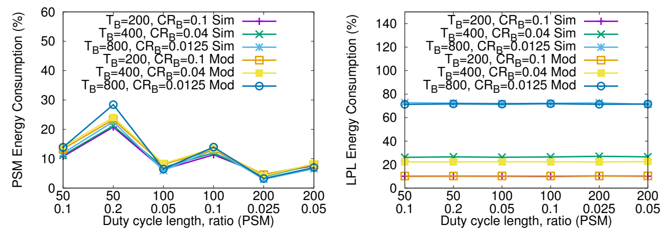

Fig. 10: Energy cost of model and simulator vs duty cycle.

for the optimization problem to numerically converge (with reasonable initial guessing). The simulation times for all tests are 10,000s, which take about one hour if the traffic is light and more than ten hours otherwise.

A. Effects of number of nodes

Measuring the performance of coexisting PSM and LPL by varying the number of devices using real hardware is prohibitive because of deployment costs, especially when tens of devices are involved. However, it is very economic to do so using the analytical model and simulator. Figure 5 and Figure 6 depict the effect on throughput and energy consumption when the number of PSM (i.e., $\{5, 10, 15, 20, 25, 30\}$) and LPL (i.e., $\{10, 20, 30\}$) devices are varied. Note that all other settings are set to their defaults. Remarkably, we observe that the results from the simulator match with those from the analysis closely. To be more specific, since the default $\lambda_W{=}5p/s$, if the number of PSM is small (e.g. 15), PSM is unsaturated even there are 30 LPL, thus its throughput equals 5. While if $W{=}30$ and $B{\geq}20$, Th_W is little less than 5 due to saturation (note that our model does not fully capture this small degradation due to its approximation nature, the improvement will be for our future works). For LPL, with the increase of # nodes, Th_B decreases due to more intensive contention. Note that the variation of W does not affect Th_B significantly because PSM nodes are in active state only for a short time in a PSM cycle. In terms of energy consumption, En_W increases with W and B, but not hugely due to the property of PSM protocol (i.e. the number of successful PSM nodes in ATIM does not change much with # active nodes). Similar results apply to En_B as well.

B. Effects of per-node offered load

Due to the significance of per-node offered load (i.e., traffic arrival rate) to the network performance, we study its effect on the throughput and energy cost. Similar as before, a scenario with 20 PSM and 20 LPL nodes with default parameters (except $\lambda_{W/B}$) are considered. We vary λ_W in $\{1, 3, 5, 7, 9, 11\}$ and λ_B in $\{0.5, 1, 3\}$ packet per second. The results obtained are depicted in Figure 7 and Figure 8 for throughput and energy consumption, respectively. Remarkably, the simulation results are in close agreement with those from the model. More precisely, when λ_W increases, if LPL is not saturated (i.e. $\lambda_B{<}3$), since PSM is not saturated, its throughput increases linearly until λ_W is near 10 (where saturation is reached). While if LPL is saturated, PSM becomes saturated when λ_W reaches 3 (because the channel is too busy with LPL transmissions), thus Th_W is almost constant for $\lambda_W{\geq}3$. For LPL, as long as $\lambda_B{<}3$ (i.e. unsaturated), $Th_B{\approx}100\%$, but if the saturation is attained, Th_B can only get 60%. Due to the same reason as described before, the variation of the offered load of PSM has very limited impact on Th_B. As for energy consumption, due to the properties of PSM and LPL protocols, En_W only increases slightly with λ_W, while En_B increases greatly with λ_B, especially when saturation is reached, En_B becomes 100% because the senders are always busy with the transmissions.

C. Effects of duty cycle settings

To analyze the impact of duty cycling length and ratio on throughput and energy usage, we investigate few different combinations of $(T_{W/B}, R_{W/B})$ with other default settings for the nodes. The combinations we use are $\{(50, 0.1), (50, 0.2), (100, 0.05), (100, 0.1), (200, 0.025), (200, 0.05)\}$ for PSM, and $\{(200, 0.1), (400, 0.04), (800, 0.0125)\}$ for LPL. The results are depicted in Figure 9 and Figure 10 for throughput and energy cost, respectively. Amazingly, the results obtained from the model agree with the simulation quite closely. In the case of throughput, when T_W is small, $Th_W{=}\lambda_W$ due to the unsaturation; while when $T_W{=}200ms$, if R_W is small (such as 0.025 here), since the ATIM is too short to send out enough packet, PSM becomes saturated (namely $Th_W{<}\lambda_W$), otherwise (like $R_W{=}0.05$), it is just enough to handle all incoming traffic, thus $Th_W{=}\lambda_W$. As saturated LPL affects PSM significantly, we can thus observe that if $T_B{=}800ms, R_B{=}0.0125$, only a small $T_W{=}50ms$ and a big $R_W{=}0.2$ can ensure a unsaturated condition for PSM. The case for LPL is similar to what we discussed before, Th_B is only around 50% when it is near saturation. In terms of energy cost, as before, for PSM, regardless of the saturation level, En_W is only slightly greater

TABLE I: Results for the performance tuning

Data arrival settings	Default values							Optimal values						
	$\boldsymbol{En}$	$\boldsymbol{Th_W}$	$\boldsymbol{Th_B}$	T_W	R_W	T_B	R_B	$\boldsymbol{En}$	$\boldsymbol{Th_W}$	$\boldsymbol{Th_B}$	T_W	R_W	T_B	R_B
λ_W=2, λ_B=0.5	**9.5%**	**2**	**98%**	100	0.1	400	0.05	**5.4%**	**2**	**92%**	300	0.02	50	0.15
λ_W=5, λ_B=1	**13.5%**	**5**	**92%**	100	0.1	400	0.05	**6.9%**	**5**	**89%**	102	0.03	50	0.15
λ_W=8, λ_B=2	**25.5%**	**5.25**	**69%**	100	0.1	400	0.05	**12.1%**	**8**	**85%**	50	0.1	50	0.15

than R_W; while for LPL, its energy cost highly depends the degree of saturation (higher value implies bigger En_B).

VII. Performance Tuning Evaluation

In this section, we evaluate the performance tuning method proposed in Section V. We demonstrate that this optimization minimizes the total energy consumption of PSM and LPL, while satisfying their throughput constraints. This evaluation is on 20 PSM and 20 LPL nodes, initially with default values for T_W, R_W, T_B and R_B, and then with the optimal values obtained from the tuning method. We inspect three scenarios in terms of data arrival rate (e.g. corresponds to temperature sensors with low traffic and fire alarm sensors with higher traffic, respectively), which are $\{\lambda_W{=}2, \lambda_B{=}0.5\}$, $\{\lambda_W{=}5, \lambda_B{=}1\}$ and $\{\lambda_W{=}8, \lambda_B{=}2\}$.

As shown in Table I, when the workload is light (e.g., $\lambda_W{=}2, \lambda_B{=}0.5$), the default duty cycling settings (namely $T_W{=}100ms$, $R_W{=}0.1$, $T_B{=}400ms$ and $R_B{=}0.05$) can offer satisfactory results. Specifically, under such condition, the total energy consumption is only 9.5% and both throughput constraints are met, however it is still not optimal. By our tuning method, the optimal settings for the four parameters are $T_W{=}300ms$, $R_W{=}0.02$, $T_B{=}50ms$ and $R_B{=}0.15$, and the corresponding energy cost is 5.4%, thus 4% more energy are saved than the default one. A more interesting case is when the traffic load becomes high (for instance, $\lambda_W{=}8, \lambda_B{=}2$), where the default duty cycling setting consumes 25.5% of the energy, and especially, the throughput constraints cannot be satisfied for both PSM (i.e. $Th_W{=}5.25{<}8$) and LPL ($Th_B{=}69\%{<}85\%$). However, the optimal settings (i.e. $T_W{=}50ms$, $R_W{=}0.1$, $T_B{=}50ms$ and $R_B{=}0.15$) generated by the tuning method yield amazingly good results, i.e., $En{=}12.1\%$, which is only half of the default. At the same time, both throughput constraints are satisfied as well. Therefore, the proposed approach is very effective in optimizing energy consumption.

VIII. Conclusions

To understand the performance of coexisting duty cycling networks with unsaturated traffic, we have presented the first analytical model to predict throughput and energy consumption for PSM and LPL. To simplify the analysis, a divide-and-conquer strategy is employed, i.e. a 2-D Markov chain stationary model is used to approximate a saturated coexistence model, which further approximates the unsaturated problem. Moreover, as an application of the model, we propose a performance tuning method that minimizes the overall energy consumption while satisfying the throughput requirements. Through extensive simulations, we demonstrate the accuracy of our analysis. Finally we show the effectiveness of the tuning method.

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