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Additional Information

DADC: A Novel Duty-Cycling Scheme for IEEE 802.15.4 Cluster-tree based IoT Applications

NIKUMANI CHOUDHURY and RAKESH MATAM, Indian Institute of Information Technology Guwahati
MITHUN MUKHERJEE*, Nanjing University of Information Science and Technology, China
JAIME LLORET, Universitat Politècnica de Valencia, Spain School of Computing and Digital Technologies, Staffordshire University, UK

The IEEE 802.15.4 standard is one of the widely adopted specifications for realizing different applications of the Internet of Things (IoT). It defines several physical layer options and Medium Access Control (MAC) sub-layer for devices with low-power operating at low data rates. As devices implementing this standard are primarily battery-powered, minimizing their power consumption is a significant concern. Duty-cycling is one such power conserving mechanism that allows a device to schedule its active and inactive radio periods effectively, thus preventing energy drain due to idle listening. The standard specifies two parameters, beacon order and superframe order, which define the active and inactive period of a device. However, it does not specify a duty-cycling scheme to adapt these parameters for varying network conditions. Existing works in this direction are either based on superframe occupation ratio or buffer/queue length of devices. In this paper, the particular limitations of both the approaches mentioned above are presented. Later, a novel duty-cycling mechanism based on MAC parameters is proposed. Also, we analyze the role of synchronization schemes in achieving efficient duty-cycles in synchronized cluster-tree network topologies. A Markov model has also been developed for the MAC protocol to estimate the delay and energy consumption during frame transmission.

CCS Concepts: • **Networks** → **Wireless personal area networks; Link-layer protocols; Sensor networks.**

Additional Key Words and Phrases: IEEE 802.15.4, duty-cycling, cluster-tree, energy conservation, synchronization, IoT

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1 INTRODUCTION

The Internet of Things (IoT) aims to inter-connect several smart devices having sensory, computing, and communication capabilities to collaboratively interact and perform several tasks autonomously. The network of such devices can be deployed in various application scenarios like smart homes, industrial monitoring and control, intelligent transportation, smart cities and healthcare. Several technologies like IEEE 802.15.4 [3], WirelessHart [14], ISA 100.11a [27], and ZigBee [1] exist that enable networking of such devices. The IEEE 802.15.4 standard is one such enabling networking technology

*Corresponding author.

Authors' addresses: Nikumani Choudhury, nikumani@iiitg.ac.in; Rakesh Matam, rakesh@iiitg.ac.in, Indian Institute of Information Technology Guwahati, Bongora, Guwahati, Assam, 781015; Mithun Mukherjee, Nanjing University of Information Science and Technology, Nanjing, China, m.mukherjee@iee.org; Jaime Lloret, Universitat Politècnica de Valencia, Valencia, Spain, School of Computing and Digital Technologies, Staffordshire University, Stoke, UK.

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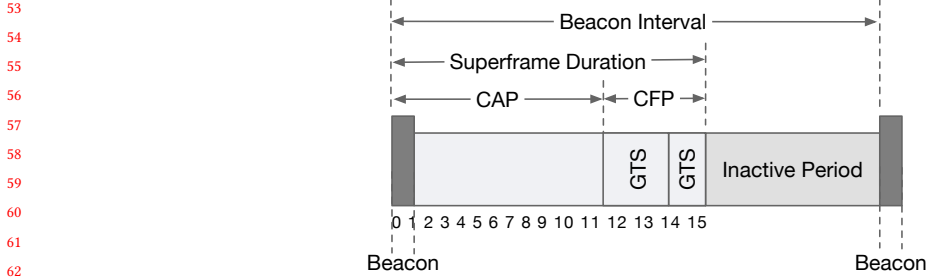


Fig. 1. IEEE 802.15.4 superframe structure [3].

that provides several physical layer options and MAC sub-layer for such IoT network applications [26, 30, 47, 48]. The standard is widely adopted for networking of devices with low-power, operating at low-data-rates, and having low-processing capabilities. The devices include Fully Functional Devices (FFDs) and Reduced Functional Devices (RFDs), together forming Low-rate Wireless Personal Area Network (LR-WPAN). FFDs can act as a coordinator and allow other devices to associate with it with the help of periodic beacons. Contrarily, RFDs are resource-constrained and act as end-devices by transmitting data to the associated coordinator. The standard supports both star and cluster-tree based network topologies. IoT applications with wide network area benefit from multi-hop set-up like cluster-tree [38]. A network adhering to the standard can operate either in beacon-enabled mode or non-beacon mode. In beacon-enabled mode, periodic beacons allow devices to synchronize their data transmissions, thereby helping them to achieve better duty-cycles. This mode is suitable for medium to large network topologies. For example, in an Industrial Internet of Things (IIoT) network, devices either transmit data periodically or to report an event/occurrence. The amount of data transmitted/received is usually low compared to a typical wireless network with limited and infrequent transmissions. Thus, allowing devices to opt for low duty-cycles.

Power consumption has always been a crucial issue for battery-powered wireless devices [31, 39, 46]. The IEEE 802.15.4 standard addresses this by defining a superframe structure [3] whereby devices periodically sleep during the inactive period. For low-power and low-data-rate network applications, this is an extremely efficient energy-saving mechanism to improve battery longevity. Synchronization [15, 17, 32, 40] between these devices is achieved with the help of the superframes in the beacon-enabled mode [3] using periodic beacons.

1.1 Superframe Structure

The superframe structure [3] is defined by two parameters, namely *macBeaconOrder* (BO) and *macSuperframeOrder* (SO). These parameters determine the duty-cycle of a device, i.e., the fraction of time for which a device is active. SO specifies the length of the active period that is the Superframe Duration (SD) during which data can be transmitted or received. The active period is divided into 16 equal duration transmission slots, consisting of Contention Access Period (CAP) and optional Contention Free Period (CFP). BO is an integer constant that determines the Beacon Interval (BI, the time interval between two successive beacons). Guaranteed Time Slots (GTS) are dedicated time slots implemented during the CFP, that allow associated devices to exclusively transmit within a portion of the superframe. The structure of a superframe is shown in Fig. 1. Not that the parameters BI and SD can be determined using the following expressions [3],

$$BI = aBaseSuperframeDuration \cdot 2^{BO} \quad (1)$$

$$SD = aBaseSuperframeDuration \cdot 2^{S0} \quad (2)$$

where, $aBaseSuperframeDuration$ is defined as the number of symbols constituting a superframe when the $S0$ is set to zero. With $0 \leq S0 \leq B0 \leq 14$ and $B0 = 15$ implies non-beacon mode [3]. To optimize power consumption, a device should refrain from idle listening, as the receiving power consumption for listening to the radio channel leads to a significant amount energy consumption, often it is assumed to be same as receiving power consumption for data packets [44].

1.2 Motivation

The IEEE 802.15.4 standard is designed for networking of power-constrained wireless devices. Therefore, adopting power conserving schemes is one of the primary objectives. Duty-cycling by devices is one of the ways by which devices can conserve energy. It is therefore essential to choose appropriate $B0$ and $S0$ values for coordinators to maximize network lifetime. The standard specifies several options that focus on minimizing energy consumption. However, it does not allow dynamic adaptation of $B0$ and $S0$ to account for varying channel conditions. Therefore, there is a necessity for dynamic duty-cycling scheme.

Existing studies [8, 29, 35, 36, 41, 42, 44, 45] in this direction are based on Superframe Occupation Ratio (SOR), buffer/queue length or delay-reliability factor. These approaches have their respective limitations. For example, the primary limitation of SOR is the over estimation of *unoccupied* portion of the superframe [16]. Also, failing to transmit the buffer/queue occupancy due to changes in network topology or if the data transmissions are not periodic, it will result in the selection of a sub-optimal active period. To address the aforementioned duty-cycling issues, a mechanism for estimating the current channel conditions is necessary for optimal duty-cycles. Further, prior works [8, 29, 35, 36, 41, 42, 44, 45] are limited to small-sized networks. Thus, considering the above factors, we develop a novel duty-cycling mechanism for cluster-tree network topologies. Additionally, to the best of our knowledge, no study has been taken up to understand the behavior of duty-cycling schemes in the presence of an operational synchronization mechanism for IEEE 802.15.4 based IoT networks.

1.3 Contributions and Organization

In this paper, a Markov model is proposed for the IEEE 802.15.4 MAC that estimates the delay and energy consumption during transmission of frames using the MAC parameters. As synchronization itself is an energy conserving process, the emphasis is on duty-cycling for further energy savings. We propose a dynamic and adaptive duty-cycling scheme that adapts superframe parameters to achieve optimal duty-cycles. The proposed scheme uses MAC parameters to account for varying channel conditions, with minimal overhead. In this work, we also show how a duty-cycling scheme benefits from a synchronization scheme. Finally, the experimental analysis showcases the performance of the proposed scheme. The main contributions of the paper are summarized as follows.

- A Markov model is presented to estimate delay and power consumption of frame transmissions.
- We analytically compute the energy spent on idle listening that can be accounted through duty-cycling in a synchronized IEEE 802.15.4 cluster-tree network.
- A dynamic and adaptive duty-cycling mechanism is proposed that uses MAC parameters to understand channel conditions and accordingly adjust $B0$ and $S0$.
- Finally, the necessity of synchronization for effective duty-cycling is presented. The trade-off between synchronization overhead and energy savings through duty-cycling, and the need for low-overhead synchronization schemes is also highlighted.

The rest of the paper is organized as follows. Section 2 presents the related work. Section 3 describes the network model considered and the proposed Markov model. Analytical study on the energy spent through idle listening is presented in Section 4. The proposed duty-cycling mechanism is described in Section 5. Sub-section 6 illustrates the role of synchronization schemes and analyze the proposed duty-cycling mechanism in presence of such synchronization schemes. The simulation and testbed results are presented in Section 7. Finally, the conclusions are drawn in Section 8

2 RELATED WORK

The IEEE 802.15.4-2011 standard is designed for low-rate, low-power communications between resource-constrained devices. It is widely adopted in various IP based applications of IoT that have flexible latency and throughput requirements [3]. Further, to support application-specific Quality of Service (QoS) requirements, the IEEE 802.15.4e [5] defines several MAC modes of operation. In [33, 34], the performance of these MAC modes are analyzed, and shortcomings are discussed. The MAC sub-layer protocols of IEEE 802.15.4e lack a complete protocol stack implementation, security, and supporting hardware [34]. Various industries [18, 25, 49], including agricultural [7, 11] and smart city [12] applications continue with IEEE 802.15.4 link layer technologies for their low-rate, low-power communication requirements. In this paper, we pursue the issue of duty-cycling for IIoT networks based on the IEEE 802.15.4 standard.

In literature, the problem of duty-cycling has been primarily approached by adapting the BO and SO parameters. In [8, 29, 35, 45], the SO parameter is tuned keeping BO fixed, while in works [41, 44], the BO parameter is adapted based on the channel traffic. In Tele-Medicine Protocol (TMP) [8], the authors initially estimate the network traffic with the help of collision probability and later compute delay and reliability factors based on the needs of remote patient monitoring systems. An optimum SD is computed that transmits the requisite data within the permissible delay. The primary design goal of Dynamic Superframe Adjustment Algorithm (DSAA) [35] is to accommodate higher traffic and minimize collisions in the channel. Application-specific collision rate and SOR are compared with the current values, and the SO parameter value is adapted accordingly. In [45], the authors presented an Adaptive Duty-Cycling Algorithm (ADCA) to adapt the active period based on the network traffic. A coordinator collects the queue length from its associated sensor devices and thereby estimates the forthcoming data traffic. Further, channel idle time and collision rate are determined and compared with threshold values. In the Duty-Cycle Adaptation (DCA) [29] scheme, coordinators are responsible for collecting both the queue delay and buffer occupancy from the associated end-devices. A combination of both of them determines the rate of incoming frames, and hence, the new SD. However, these approaches [8, 29, 35, 45] add both transmission and computational overhead to the network. Moreover, the range of adapting the duty-cycle is reduced as SO is limited by BO ($SO \leq BO$). Computation of SOR based on the number of frames received can be ambiguous as it may either mean low traffic or high collisions in the network, resulting in low throughput. Schemes such as [29, 36, 45] rely upon sensor devices' queue length or buffer to estimate forthcoming network traffic in a static network. But, in dynamic network topologies as well as in aperiodic data generations, such estimations may fail to be reasonably accurate.

The main focus of Beacon Order Adaptation Algorithm (BOAA) [41] is to lower the duty-cycle of a coordinator. It works on the premise that if the highest transmitting device transmits at a lower rate than a predefined threshold, then there is a frequent transmission of beacon frames. Adaptive Optimal Duty-Cycling (AODC) [44] algorithm also adapts its BO parameter value by solving an optimization problem. The scheme solves an objective function while minimizing constraints like delay and power consumption and maximizing reliability. One of the main limitations with the tuning of BO parameter value is the loss of synchronization among the devices. A longer BO results in high delay and high contention at the beginning of the next superframe cycle.

209 The authors in [20, 21, 42] utilize both B0 and S0 parameters to adapt the duty cycle at the coordinator devices.
210 They address the deficit incurred while adapting only a single parameter by providing the flexibility of choice and
211 range for dynamic duty-cycling. In Dynamic Beacon Interval and Superframe Adaptation Algorithm (DBSAA) [42],
212 B0 and S0 parameter values are adapted based on SOR, collision ratio, the number of frames successfully received,
213 and the number of transmitting device. These values are computed after a regular interval of beacon frames. It is
214 suitable for networks with high duty-cycle requirements. Duty-Cycle Learning Algorithm (DCLA) [20] is based on
215 reinforcement learning model, where initial parameters are estimated by idle listening, packet accumulation, and delay
216 in end-devices' transmitting queues. Later, there is repetitive interaction with the sensor devices, and the duty-cycle
217 is adapted iteratively until an optimal duty-cycle is reached fulfilling the application needs. However, in dynamic
218 channel traffic, frequent adaptation in duty-cycle results in high overhead in the network. Recently, to prolong the
219 longevity of the device battery works like [19, 28, 37, 43, 50] have been proposed that use wake-up radio, residual
220 energy of devices, learning-based algorithms, GTS-based mechanisms, combining with data rate (link adaptation) and
221 signal-to-noise-ratio.
222
223
224

225 A considerable overhead is incurred through duty-cycling [17] in a synchronized IEEE 802.15.4 based cluster-tree
226 network topology. Duty-cycling schemes [19, 29, 35, 36, 45] are invoked at every BI that results in the overhead of
227 recomputing B0 and S0 parameter values. Note that DBSAA address this issue by triggering the duty-cycling mechanism
228 after a fixed interval of BI. Also, learning-based mechanisms [20] involve several steps before reaching an optimal state.
229 In addition, most of these works are suitable for small-sized network topology like star topology.
230

231 Finally, with the inclusion of IEEE 802.15.4e MAC modes, works like [23, 24] have been carried out to improve slot
232 allocations in Time-Slotted Channel Hopping (TSCH) mode of operation. Orchestra [23] schedules slots (shared and
233 dedicated) for traffic flows in 6tisch networks by exploiting Routing Protocol for Low-power and Lossy Networks (RPL)
234 routing. However, it is not adaptive to a change in the traffic rate on the channel. The authors in [24] proposed an
235 adaptive slot allocation mechanism on top of an existing schedule to activate a set of their allocated slots. The proposed
236 mechanism facilitates the use of an optimal number of slots for transmissions and allows the device to enter the sleep
237 state for the remaining allocated but unused slots. Moreover, these unused slots can be activated during high traffic
238 flows. However, it assumes that excessive over-allocation is performed during the scheduling of slots, and the scheme
239 cannot further increase the number of slots allocated during schedule formation. The authors state that the proposed
240 scheme does not apply to busy TSCH networks that can handle very high traffic bursts.
241
242
243

244 In view of this, we address the issues related to duty-cycling for cluster-tree topologies in IEEE 802.15.4 networks
245 using the MAC parameters (`macMinBE`, `macMaxCSMABackoffs`, and `macMaxFrameRetries`). These MAC parameters are
246 the true indicator of the channel condition through which the data transmissions take place. Also, the paper presents
247 the efficiency of a duty-cycling scheme in the presence of an operational synchronization mechanism.
248

249 In [16], we presented a preliminary version of the proposed duty-cycling algorithm. The differences between this
250 work and [16] are as follows: 1) This paper presents the scope and necessity of duty-cycling mechanisms for additional
251 energy savings in synchronized cluster-tree network topologies. 2) Synchronization mechanism assisting duty-cycling
252 schemes by improving their efficiency is presented. We further present an analysis of the proposed duty-cycling
253 mechanism in the presence of several synchronization schemes. Such analysis was not present in the earlier version [16].
254 3) Finally, we present more detailed experimental results of the proposed duty-cycling algorithm by setting up a testbed
255 along with simulations.
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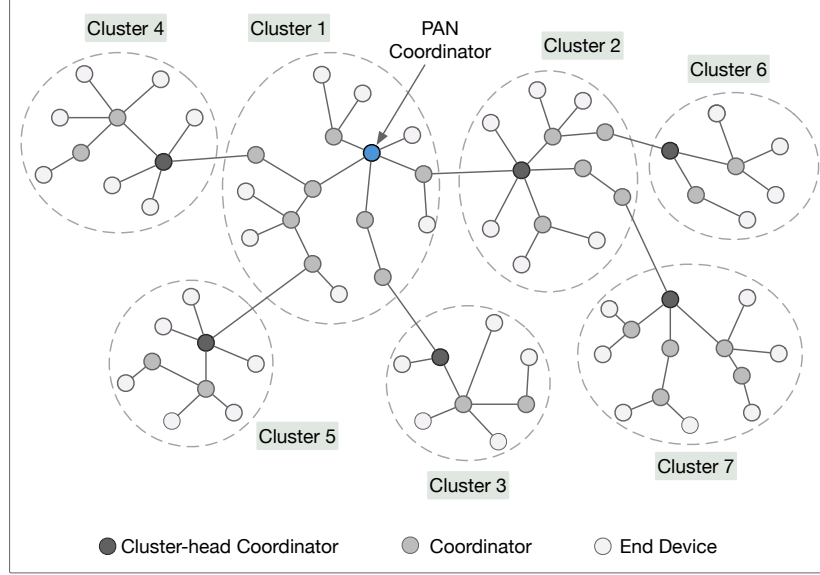


Fig. 2. Cluster-tree topology.

3 SYSTEM MODEL

3.1 Network Model

In this paper, an IEEE 802.15.4 based cluster-tree network topology is considered, as shown in Fig. 2. The topology comprises of coordinator and end devices. A PAN Coordinator (PANC) that is chosen among the set of coordinators, acts as the overall coordinator of the network. Periodic beacons are used by the coordinators to synchronize their transmissions in a non-overlapping manner. The end devices associate with a neighboring coordinator and transmit their sensed data to the associated parent coordinator. A group of coordinators and devices form a cluster. For operational simplicity, a cluster-head is chosen at each cluster. The duty-cycles of the coordinators are set during the network initialization. However, the B0 and S0 parameter values may not be optimal. In this paper, MAC parameters (defined in the standard) like `macMinBE`, `macMaxCSMABackoffs`, and `macMaxFrameRetries` are used to achieve dynamic duty-cycling. These parameters can best describe the present channel condition based on which duty cycle can be adapted accordingly. The main notations in this paper are summarized in Table 1.

3.2 Proposed Markov Model

To estimate the transmission time and energy consumption in the IEEE 802.15.4 MAC, a Markov model is presented. We consider an IEEE 802.15.4 cluster-tree network topology. We assume that n nodes have uplink traffic to be transmitted through its parent coordinator. We further consider a beacon-enabled network with a slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm in practice. Superframe structure is used by the parent coordinators that governs the transmissions by the nodes. It is assumed that loss of frames is due to collisions in the network for which retransmissions take place. Nodes perform Clear Channel Assessment (CCA) when they have data to transmit, and the probability of such an event is independent of any other node in the network.

Table 1. Main Notation Definition

Symbols	Definition
T_{BCK_n}	The time spent at the n th backoff stage.
T_{CCA}	The time required for performing CCA.
ρ_{success}	The probability of successful transmission.
λ	Packet generation rate in every beacon interval.
T_i	The total transmitting time for the i th device.
$T_{\text{ACK_rec}}$	Time spent in receiving the ACK frame.
$T_{\text{ACK_wait}}$	Time spent in waiting for the ACK frame.
T_{beacon}	The transmission time for beacon frames.
$T_{\text{coordinator}(C)}$	The transmission time for a coordinator.
T_{busy}	Total transmitting and receiving time for a coordinator.
$T_{\text{idle-period}}$	The time spent in idle listening by a coordinator.
$E_{\text{idle-period}}$	The energy spent in idle listening by a coordinator.
$E_{\text{saved-dc}}$	The actual energy saved using duty-cycling.
E_{tx}	Energy consumed to transmit a frame.
E_{rec}	Energy consumed to receive a frame.
E_{sleep}	Energy spent during sleep period.

The proposed Markov model for IEEE 802.15.4 CSMA/CA MAC is presented in Fig.3. The model is depicted with several states and each state is represented by a 4-valued tuple $(i, j, \text{CCA}, \text{rnd})$, where $i = 0, \dots, 7$ indicates the `macMaxFrameRetries` parameter, $j = 0, \dots, 5$ represents the `macMaxCSMABackoffs`, and rnd signifies the random wait in a backoff stage, ranging from 0 to $2^{BE} - 1$. A node transits from its idle state to its first backoff state with a probability, $\rho = 1$. According to the IEEE 802.15.4 CSMA/CA, two CCAs (termed `CCA_1` and `CCA_2`) are to be performed by a node before transmission. `CCA_1` must result to channel free prior to proceeding for `CCA_2`. That is, a node must twice sense the channel as free before transmitting a frame. If `CCA_1` results in channel busy, a node transits to the next backoff state. Otherwise, `CCA_2` is performed. Again, if the node senses the channel to be busy through `CCA_2`, the node transits to the next backoff state. On the other hand, if `CCA_2` results in channel free, i.e., the node senses two successive channel accesses as free, the frame is transmitted on to the channel or medium. If a node fails to transmit (multiple channel busy), the node transits to the failed state. In IEEE 802.15.4 CSMA/CA, after transiting to five (default) successive backoff states, channel access failure is declared. The model also accommodates both acknowledgment and frame retransmission. A successful transmission (on acknowledgment receipt) implies a transition back to the idle state wherein the node is ready for the next transmission. An unsuccessful transmission (denoted by failure state in Fig 3) results in a retransmission attempt by the node. However, a limit is set for the number of such attempts. On exceeding the specified limit of retransmissions, the transmission is declared as failed. For a retransmission, the state changes are a repetition of the entire transmission procedure. The minimum transmitting time, $T_{\text{tx_min}}$, required by a device for transmitting a single frame from the backoff state is:

$$T_{\text{tx_min}} = \sum_{i=1}^n T_{\text{BCK}_n} + nT_{\text{CCA}_1} + T_{\text{CCA}_2} + T_{\text{ta}} + T_l + T_{\text{ACK_wait}} + T_{\text{ACK_rec}}, \quad (3)$$

where T_{BCK_n} is the time spent in the n th backoff state before attempting the first CCA. T_{CCA_1} and T_{CCA_2} are time required in `CCA_1` and `CCA_2`, respectively, T_{ta} is the turn around time, T_l is the time for transmitting a frame of length l .

Maximum transmitting time, $T_{\text{tx_max}}$, (assuming backoff occurs after `CCA_2`) is given by

$$T_{\text{tx_max}} = T_{\text{tx_min}} + (n - 1)T_{\text{CCA}_2}. \quad (4)$$

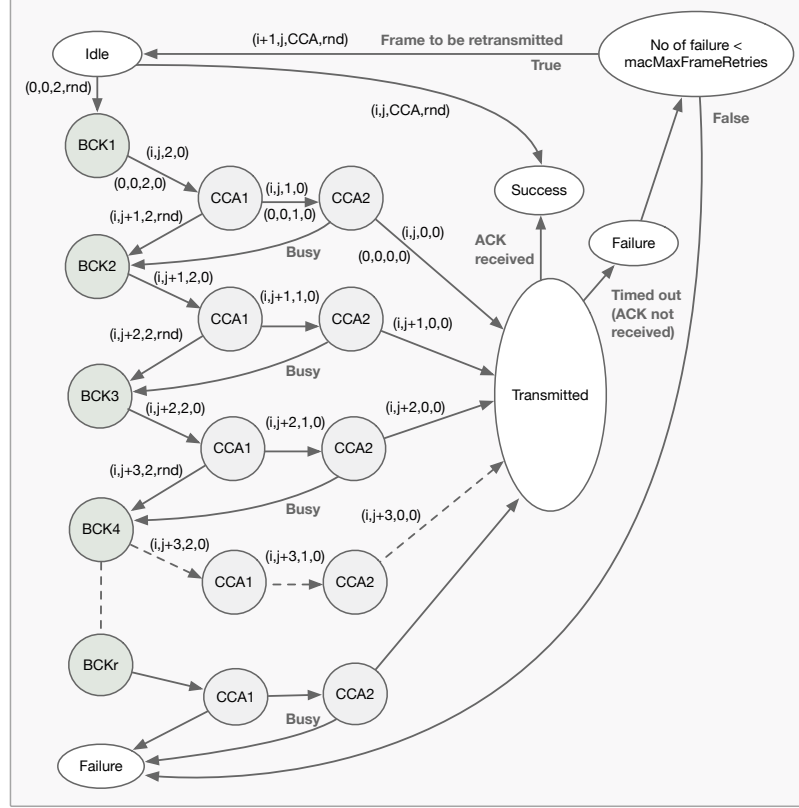


Fig. 3. Markov Model for IEEE 802.15.4 CSMA/CA.

Now, transmission time of a frame from the first backoff state, T_{tx_1} , (without sensing any channel busy) is given by,

$$T_{tx_1} = T_{BCK_1} + T_{CCA_1} + T_{CCA_2} + T_{ta} + T_l + T_{ACK_wait} + T_{ACK_rec}. \quad (5)$$

Hence, the time required for frame reception will be $T_{tx_1} - (T_{ACK_wait} + T_{ACK_rec})$.

For a single transmission, the energy consumed is expressed as,

$$E_{tx_min} = E_1 + (n - 1)E_{rec}T_{CCA_1}. \quad (6)$$

$$E_{tx_max} = E_1 + (n - 1)E_{rec} (T_{CCA_1} + T_{CCA_2}), \quad (7)$$

where E_{rec} is the energy required for completing an operation and E_1 is given as

$$E_1 = E_{rec} (T_{CCA_1} + T_{CCA_2}) + E_{ta}T_{ta} + E_{tx}T_l + E_{rec} (T_{ACK_wait} + T_{ACK_rec}). \quad (8)$$

For expressing retransmissions, denoted by i in the Markov model, the aforementioned equations need to be multiplied by the number of retransmissions for that particular frame.

The above expressions give us upper bound and lower of transmission time and energy consumption in an IEEE 802.15.4 MAC. These expressions can also be used to compute the total cost of transmissions in terms of energy accurately using probabilistic analysis.

4 ANALYSIS OF IDLE LISTENING

In this section, the analytical approximation of the energy spent during idle listening is presented. Devices transmit their data to the PANC through their parent coordinator in a multi-hop fashion. In our analysis, we take into account the optional acknowledgement frames as well as retransmission of unsuccessful frames. Let the number of data transmitting devices in the network be N . As per the standard, a device can transmit data frames only after finding the channel free for two successive CCA, CCA_1 and CCA_2. The probability of such an event is denoted by ρ_{success} . Let λ be the packet generation rate at every BI. Therefore, the time spent by a device i , for transmission in a single BI is expressed as,

$$T_i = \rho_{\text{success}}(N) \times \lambda (T_{ta} + T_l). \quad (9)$$

A coordinator will spend time T_i for frame reception from an associated device, i .

The transmission time for each device at every BI is independent of the total number of devices in the network. Contention in the channel may only delay (due to channel busy) access to the channel. Thus, total transmitting time for n_{child} devices to a coordinator is given by,

$$T_i(N) = \sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \times \lambda (T_{ta} + T_l). \quad (10)$$

A coordinator also transmits beacon frames at the beginning of each BI. Further, ACK (acknowledgement) frames are transmitted against successful reception of frames from its N child devices. Hence, the transmitting time for the coordinator is,

$$T_{\text{coordinator}}(C) = T_{\text{beacon}} + \sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \times T_{\text{ACK_tx}}, \quad (11)$$

where $T_{\text{ACK_tx}}$ is the transmission time for ACK frames. T_{beacon} is the duration of the beacon frame transmission. Now, total busy period of the coordinator is given by,

$$\begin{aligned} T_{\text{busy}} &= T_i(N) + T_{\text{coordinator}}(C) \\ &= \left(\sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \times \lambda (T_{ta} + T_l) \right) + \left(T_{\text{beacon}} + \sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \times T_{\text{ACK_tx}} \right) \\ &= \sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \left(\lambda (T_{ta} + T_l) + T_{\text{ACK_tx}} \right) + T_{\text{beacon}}. \end{aligned} \quad (12)$$

Hence, the idle period of the coordinator can be expressed as,

$$\begin{aligned} T_{\text{idle-period}} &= \text{SD} - T_{\text{busy}} \\ &= \text{SD} - \sum_{i=1}^{n_{\text{child}}} \rho_{\text{success}}(N) \left(\lambda (T_{ta} + T_l) + T_{\text{ACK_tx}} \right) - T_{\text{beacon}} \end{aligned} \quad (13)$$

From the above expression, the energy spent in idle listening can be given by,

$$E_{\text{idle-period}} = E_{\text{rec}} \times T_{\text{idle-period}}. \quad (14)$$

Table 2. Energy consumption of coordinator

Coordinator State	Energy Consumption
Transmitting	$E_{tx} \times T_{\text{coordinator}}(C)$
Receiving	$E_{rec} \times T_i(N)$
Idle Listening	$E_{rec} \times T_{\text{idle-period}}$
Sleeping	$E_{\text{sleep}} \times T_{\text{sleep}}$

For low-power network topologies, the primary objective is to minimize the energy spent in idle listening. This is achieved through duty-cycling. In other words, a duty-cycling scheme can reduce $E_{\text{saved-dc}}$ amount of energy, where $E_{\text{saved-dc}} \leq E_{\text{idle-period}}$.

4.1 Role of B0 and S0 in IEEE 802.15.4 based networks

In power constrained wireless networks, battery-powered devices deplete a major portion of their energy through idle listening. The severity of the problem compounds in IEEE 802.15.4 based networks as the standard suggests fixed B0 and S0 parameters, resulting in sub-optimal duty-cycles. In order to overcome this, optimal B0 and S0 have to be chosen to lower the undesirable energy dissipation. Hence, it is necessary to analyze the impact of these parameters on the idle listening and energy consumption of a coordinator. To analyze this, a cluster-tree network topology is considered, as shown in Fig. 2. The value of the parameter (S0) is altered to observe the energy dissipation in the network. The objective of the following experiments is to identify the scope of a duty-cycling algorithm by varying different parameters. S0 is varied to resemble different operating scenarios of a coordinator with different active periods. On the other hand, data transmissions are increased to understand the role of the duty-cycling mechanism under varying channel conditions. We use the energy consumption at the four states (Table 2) of the coordinator (transmitting, receiving, idle listening, and sleeping) to understand the need for a duty-cycling mechanism. The experiments are performed in the network simulator ns2 [2] with parameters summarized in Table 3.

Initially, we start with $S0 = 2$ and increment gradually to $S0 = 8$ for analyzing the variations experienced by the coordinator at each state. The other parameters, like B0, data frame size, and network size remain constant for varying S0. The percentage time spent by the coordinator nodes in their four states is recorded. The amount of idle listening is observed to increase with the increase in the active period of the coordinators, as shown in Fig.4a. The sleep period decreases, but there is no effect on the frame reception and transmission time as no extra frames are introduced in the network. From the energy consumption point of view (as shown in Fig.4b), this is the major source of energy wastage where a coordinator keeps its transceiver radio ON throughout the active period without receiving or transmitting any frame. This primarily contributes to the total energy consumption of the coordinator. Duty-cycling schemes can largely contribute to lowering this energy wastage by selecting an optimal S0 for the coordinators in the network.

To increase the channel traffic, we scale the network by adding new data-generating devices, and the other parameters are kept fixed. With an increase in the number of transmitted frames, the time spent in idle listening decreases, whereas time spent in transmitting and receiving state increases, as shown in Fig.4c. There is no change in the sleeping time as S0 and B0 are fixed. Further increase in network size will have no effect on these states as the active period is completely occupied in receiving frames. From the energy consumption point of view (as shown in Fig.4d), the total energy consumed increases linearly with the network size until the active period is fully occupied. Afterward, a surge in energy consumption is observed arising from collisions and retransmissions of frames. Also, it may be noted that high contention results in higher latency in transmissions. Presence of a duty-cycling scheme will allow the coordinators to adapt their B0 and S0 parameters based on the current channel traffic. This will ensure optimal energy consumption,

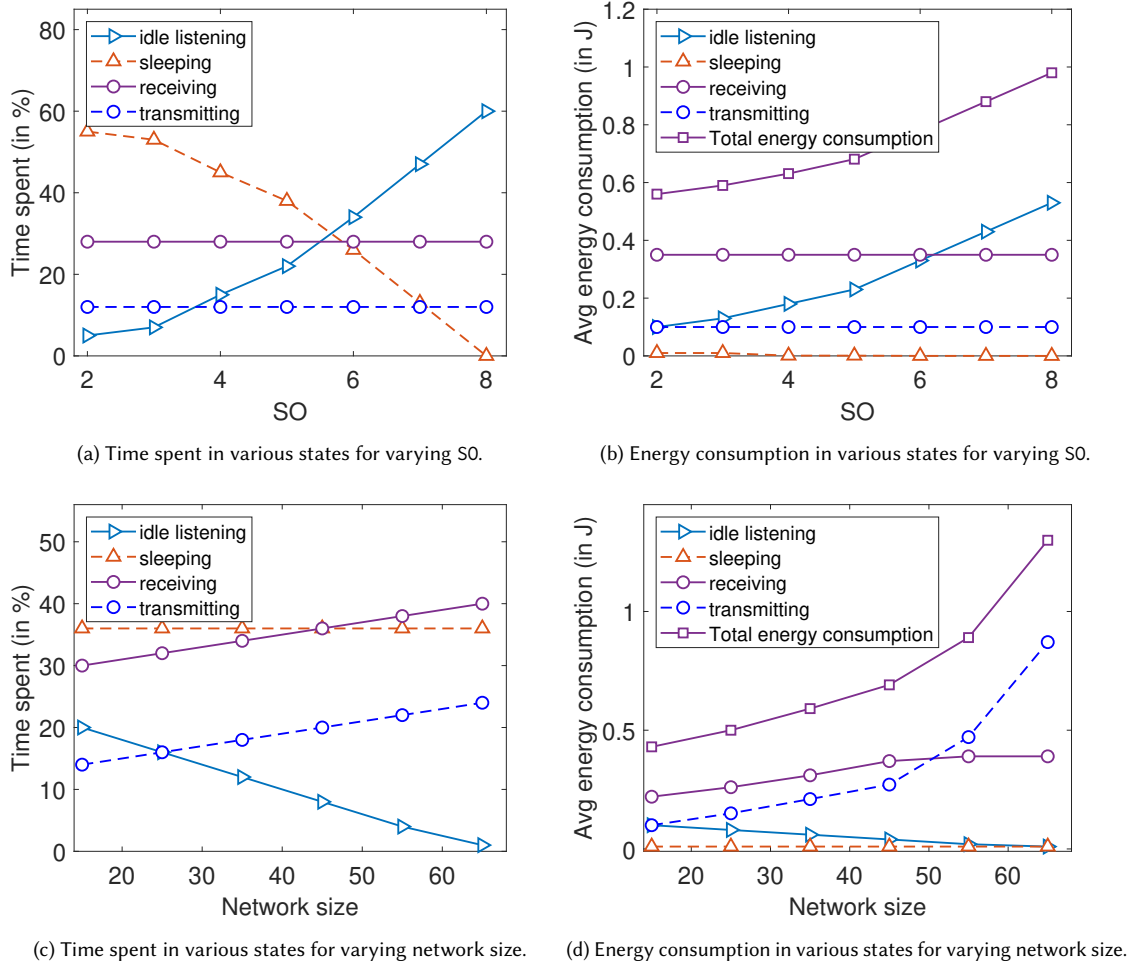


Fig. 4. Simulation results depicting the role of B_0 and S_0 parameters in optimizing energy consumption.

higher frame delivery ratio, and lower latency. A duty-cycle scheme should be able to accurately identify changes in channel contention and accordingly act upon it to optimize the B_0 and S_0 values of the coordinators. As discussed earlier, approaches considered by prior works [8, 29, 35, 36, 41, 42, 44, 45] has several limitations in estimating the channel traffic. In view of this, we propose a novel mechanism to estimate the channel contention in the network with direct use of the parameters that govern the channel state information.

5 PROPOSED DYNAMIC & ADAPTIVE DUTY-CYCLING ALGORITHM

We aim to propose an adaptive duty-cycling algorithm that optimizes the superframe parameters of a coordinator based on channel conditions. This is done using MAC parameters, namely, $macMinBE$, $macMaxCSMABackoffs$ and $macMaxFrameRetries$. The CSMA/CA variables BE (Back-off Exponent), NB (Number of Back-off) and NR (Number of

Retransmissions), respectively are used to hold the current values of the above said MAC parameters. These parameters are used to gather the current channel state information.

5.1 MAC parameters for channel state information

Optimal MAC parameter settings determine the reliability, latency, and energy consumption of a coordinator. These parameters act as an indicator of contention in the channel. The MAC behavior is regulated by the parameters described below.

- **macMaxBE:** (Range: 3-8, Default: 5) This parameter value implies the maximum value of the backoff window exponent. A higher value of this parameter increases the range of the backoff window by allowing **macMinBE** the scope to set a higher value for the CSMA/CA variable *BE*. In other words, **macMaxBE** defines the upper bound for the **macMinBE** parameter.
- **macMinBE:** (Range: 0-**macMaxBE**, Default: 3) This parameter value signifies the minimum value of the backoff window exponent. Increasing its value lowers the probability of finding the channel busy. This is due to an increase in the window size of the backoff, leading to the transmission attempts being spread over a larger size. However, a higher value of the parameter can lead to longer wait in the backoff state, resulting in higher latency. The upper limit of the parameter **macMinBE** depends upon **macMaxBE**. A higher value for **macMaxBE** allows a wider range for **macMinBE**. The variable *BE* is initialized to **macMinBE** or 2 (whichever is minimum) and is incremented by one each time the channel is found busy till *BE* equals **macMinBE**. Depending on the value of *BE*, a node waits for a random amount of time $(0-2^{BE}-1)$ prior to sensing the channel.
- **macMaxCSMABackoffs:** (Range: 0-5, Default: 4) This parameter value signifies the maximum number of backoff the CSMA/CA algorithm will attempt before declaring a channel access failure. Increasing its value allows more number of transmission attempts after a CCA busy. This way it complements the **macMinBE** parameter. A higher value of this parameter is an indication of high contention in the channel. The CSMA/CA variable *NB* keeps a count of the number of backoffs a node has encountered while attempting a transmission. Each time the node senses the channel to be busy (through CCA_1 or CCA_2), *NB* is incremented by one. When the count breaches the **macMaxCSMABackoffs** value, channel access failure is declared.
- **macMaxFrameRetries:** (Range: 0-7, Default: 3) This parameter value denotes the maximum number of retransmissions permitted following a failed transmission. A higher value of this parameter means a higher probability of successful transmission as the basic transmission mechanism is repeated when frames are dropped due to channel errors or the occurrence of a collision. It leads to repetition of the entire procedure of **macMinBE** and **macMaxCSMABackoffs** parameters. The CSMA/CA variable *NR* is responsible for maintaining the count of the number of retransmission attempts made by a node. *NR* is incremented by one for every new attempt to retransmit a failed frame till it exceeds the **macMaxFrameRetries** value. The other CSMA/CA variables like *BE* and *NB* are reset on each increment of *NR*. The parameter **macMaxFrameRetries** has a major contribution to the power consumption of a node, as compared to the other MAC parameters [22]. This is due to the repetition of the channel access mechanism multiple times. A significant energy is consumed for transmitting a frame whenever a collision or a channel error occurs.

The standard defines the range of values for all the MAC parameters. It further recommends default values for each of the parameters for an LR-WPAN. Few works [10, 13] have suggested the dynamic setting of the MAC parameters; however, in this paper, we consider the standard defined default MAC parameter values. In addition, every node in

Algorithm 1: DADC: Dynamic and Adaptive Duty-Cycling

```

625 Algorithm 1: DADC: Dynamic and Adaptive Duty-Cycling
626
627 1 Retrieve  $BE$ ,  $NB$ ,  $NR$  from received frames;
628   if  $\left(NB \leq \left\lfloor \frac{macMaxCSMABackoffs}{2} \right\rfloor\right)$  then
629     2    $SO = SO - 1$ ;
630     3   if  $\left(NR \leq \left\lfloor \frac{macMaxFrameRetries}{2} \right\rfloor \&\& BE \leq \left\lfloor \frac{macMaxBE}{2} \right\rfloor\right)$  then
631       4      $BO = BO + 1$ ;
632       else
633         5     Continue with the current superframe parameter values;
634       end
635     end
636   else
637     6     if  $(NB = macMaxCSMABackoffs)$  then
638       |    $SO = SO + 1$ ;
639     else
640       7     Continue with the current superframe parameter values;
641     end
642   end
643
644
645

```

646 the network maintains its own set of the CSMA/CA variables [3]. A parent coordinator retrieves the set of current
647 CSMA/CA parameter values from its associated nodes, compares with the respective MAC parameters and learns the
648 level of contention in the channel. Thus, these parameters are employed in the proposed duty-cycling algorithm to
649 adapt the BO and SO values of a coordinator.
650

651 5.2 Dynamic and Adaptive Duty-cycling (DADC) scheme

652 In this section, we propose a Dynamic and Adaptive Duty-Cycling (DADC) mechanism that improves network lifetime
653 and optimizes network performance. It is executed at each of the coordinators in the network. A coordinator initiates
654 the algorithm by retrieving the current values of the CSMA/CA parameters from the received frames and then computes
655 their mean. Since each device maintains all these values for each transmission [3], there is no need to define any new
656 parameter. The current parameter values can be transmitted along with the MAC payload. For every coordinator, we
657 define an array (size three) to store BE , NB , and NR values transmitted by the associated devices. The coordinator adds
658 up the parameter value collected from all the devices and maintains the mean value in the respective array cell. The
659 proposed algorithm may either be invoked after every superframe cycle (BI) or after a fixed predefined set of BI (α).
660 The computed mean is compared with the standard defined default values. These are the benchmark values for optimal
661 performance in LR-WPAN with flexible throughput and latency requirements.
662

663 The superframe parameters, BO and SO , are adapted using Algorithm 1. During low channel contention, coordinators
664 adapt its superframe parameters to enable longer sleep cycles. Only SO is decremented when the NB is low, but NR
665 (retransmissions) value is found to be high. A higher NB value suggests high contention in the channel, whereas, higher
666 NR can be attributed to collision among frames. In line 2, to achieve low duty-cycle, the active period is reduced without
667 altering the BI . Duty-cycle can be further lowered if the number of retransmissions and BE values are low (signifying
668 low contention in the channel) as seen in line 4. As observed through line 6, if a device encounters several backoffs
669 during transmission that indicates an increased channel contention, then the SO is incremented. This assures a larger
670 window for transmissions to the coordinator. The new set of BO and SO parameters are announced to the associated and
671

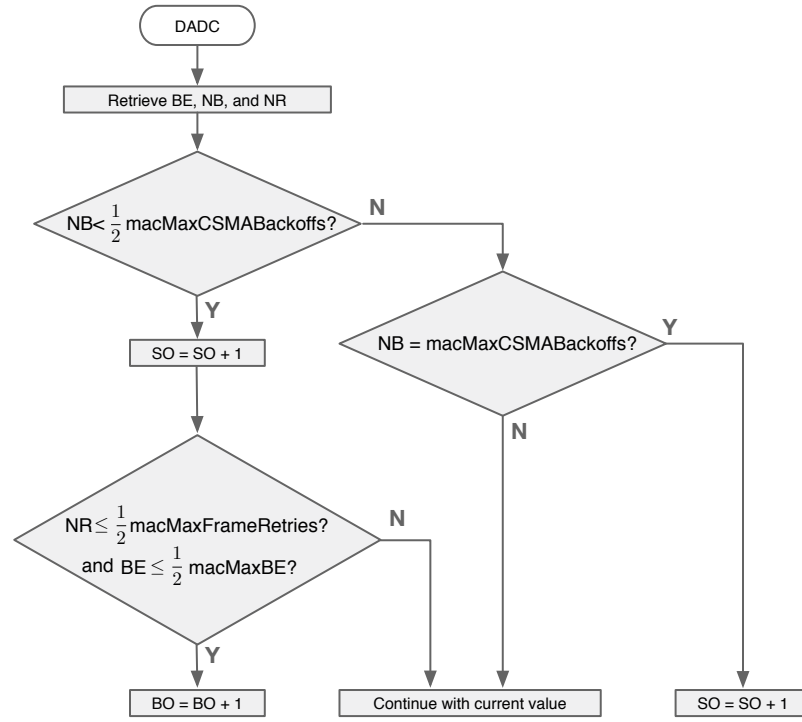


Fig. 5. Flowchart for the DADC algorithm.

neighboring devices through the periodic beacons. DADC do not alter the $B0$ and $S0$ values if the retrieved CSMA/CA values (BE , NB and NR) are closer to the default MAC parameter values. It implies that the network is operating under optimal duty-cycle for the coordinators and the channel contention is ideal for a LR-WPAN. Also, the constraint for the superframe parameter values ($0 \leq SO \leq BO \leq 14$) is to be maintained [3].

While the work in [35, 42] computes SOR, and [20, 29, 36, 45] determines queue state and buffer occupancy of the associated devices, DADC uses the standard defined MAC parameters. Computing SOR, collision rate and idle period at every BI is an overhead to the network that is avoided in DADC. Also, the proposed algorithm focuses on applications that have relatively flexible latency and throughput requirements. It primarily aims to achieve low duty-cycles to increase the overall network lifetime, similar to [41]. However, the authors in [20, 29, 35, 36, 42, 45] adapt the duty-cycle to maintain QoS requirements like throughput and latency through predefined thresholds. Also, DADC is quick to respond during changes in channel contention while the aforementioned prior works wait for the computed value to exceed the threshold. Finally, DADC induces superframe parameter changes only if the current CSMA values are either quite low or equal to the maximum limit (default values) of the respective parameter values. Otherwise, the channel operates under optimal contention, and thus, no changes to the $B0$ and $S0$ values are caused. Such a situation leads to a stable phase for the DADC algorithm. In IIoT, dynamic traffic (high and low bursts) is not a regular occurrence, and hence it is necessary for the network to achieve stability in parameter settings. This also reduces the overhead associated with duty-cycling and re-synchronization [15].

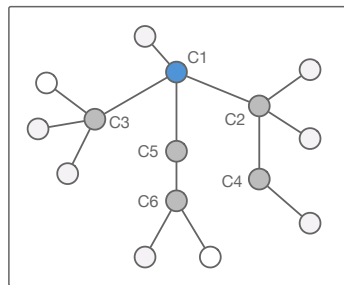


Fig. 6. Example network.

6 SYNCHRONIZATION ASSISTING DUTY-CYCLING

A duty-cycling algorithm adapts the BO and SO parameters of a coordinator to optimize its sleep schedule. The changes in these parameters are typically communicated to the associated coordinators via beacons. In a cluster-tree network, synchronization among multiple such coordinators is necessary to compute non-overlapping transmission schedules. In the absence of such a synchronization scheme, the changes in BO and SO of one coordinator often impact the transmission of other coordinators, which offset the overall gains of duty-cycling. In other words, a duty-cycling scheme affects the synchronization of devices, but, with an assisting synchronization scheme, the benefits of duty-cycling increase multi-fold. To illustrate this, we consider a network as shown in Fig. 6. A transmission schedule computed by C1, C2, C3, and C4 as per Localized Beacon Synchronization (LBS) [15], is shown in Fig. 7(a). Through duty-cycling, coordinator C1 that adjusts its SO causes an overlapping transmission slot with C2, shown in Fig. 7(b). If the affected coordinators do not recompute their transmission schedules, collisions will recur. The energy spent on handling recurring collisions and retransmissions would continue to increase with coordinators frequently adapting their duty-cycles. Therefore, the energy gains via duty-cycling would become insignificant. To avoid this, the assistance from a synchronization scheme becomes crucial as it recomputes the transmission schedules of associated coordinators (as shown in Fig. 7(c)), if they happen to lose synchronization. Therefore, the role of synchronization is critical in maximizing the benefits of duty-cycling. On the other hand, there is also an overhead associated with synchronization. Practically, the energy savings via duty-cycling must be higher compared to the energy spent on re-synchronization.

To analyze the trade-off between synchronization overhead and energy savings through duty-cycling, we consider the same example network, as shown in Fig. 6. Let C1 adapt its BO and SO parameters, which results in loss of synchronization with the other neighboring coordinators (C2, C3, C4, C5, and C6). The amount of energy conserved via duty-cycling by C1 is given by $E_{\text{saved-dc}}$. To re-synchronize all the coordinators, a re-synchronization overhead, $E_{\text{sync_overhead}}$ is incurred. Centralized synchronization schemes are observed to incur higher overhead than distributed schemes [17]. A centralized scheme recomputes the transmission offset of all the coordinators, whereas, a distributed scheme will recompute up to 2-hop neighbors. In the considered topology, a re-synchronization overhead (distributed approach) of $2 \times 5 \times r$ [15] is incurred, where r denotes the transmission data-size (in byte) during the synchronization process. In an ideal scenario, $E_{\text{saved-dc}}$ should be higher than $E_{\text{sync_overhead}} = 10r$; otherwise, the network is not benefited from the presence of a synchronization scheme. Alternatively, a duty-cycling scheme may compute the associated re-synchronization overhead prior to adapting the BO and SO values to trade-off the energy gain through duty-cycling. But to compute $E_{\text{saved-dc}}$ accurately is itself an overhead to the network. To maximize the energy gain through duty-cycling at C1, two approaches can be considered. First, the duty-cycling should not affect the synchronization

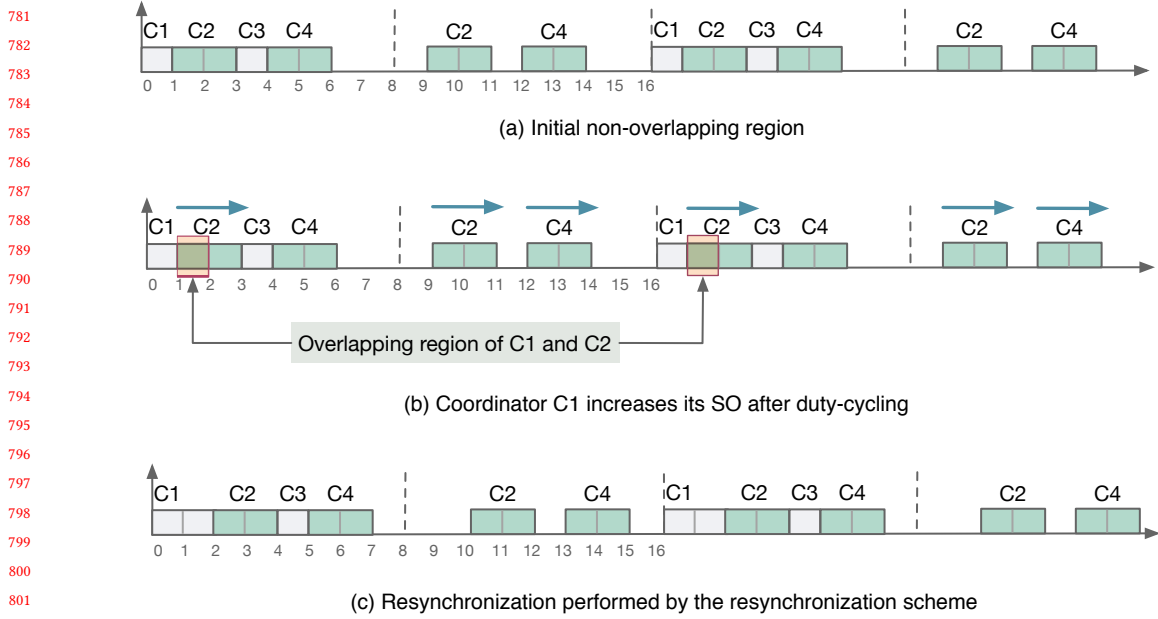


Fig. 7. Synchronization scheme assisting duty-cycling mechanism.

among the other coordinators. In such a scenario, duty-cycling at C1 does not affect the existing transmission schedule of other coordinators. Hence, the re-synchronization overhead of $10r$ is not incurred and the total energy gain after duty-cycling at C1 will be $E_{\text{saved-dc}}$. Second, operating a low-overhead synchronization scheme alongside the duty-cycling mechanism. The objective is to further reduce $E_{\text{sync_overhead}}$. The re-synchronization mechanism needs to effectively minimize the necessity of recomputing the entire transmission schedule. It should select fewer coordinators that require shifting of their transmission slots while allowing the remaining coordinators to use their current beacon transmission slots. For instance, duty-cycling at C8, would result in $E_{\text{sync_overhead}} = 0$. Such a low-overhead re-synchronization mechanism has been presented in [15].

7 EXPERIMENTAL RESULTS

The performance results of the proposed algorithm are presented using both simulations and experiments in a real testbed.

7.1 Simulation Results

We use the network simulator NS-2.34 [2] to evaluate the performance of existing synchronization schemes along with the DADC mechanism. Further, the performance of DADC is evaluated and compared with other duty-cycling schemes. Parameters that are used in the experiments are listed in Table 3. The coverage area of the considered topology is $100\text{m} \times 100\text{m}$. The 2.4GHz frequency band is selected as it provides the maximum data rate of 250kbps [3]. The simulation duration is fixed at 3000 seconds duration. For any given combination of simulation parameters, we ran 30 different simulations and finally averaged over all the 30 different results. The two-ray ground radio propagation model and IEEE 802.15.4 PHY and CSMA/CA for MAC sub-layer are used for our simulation. A cluster-tree comprising of seven

Table 3. Simulation Parameters

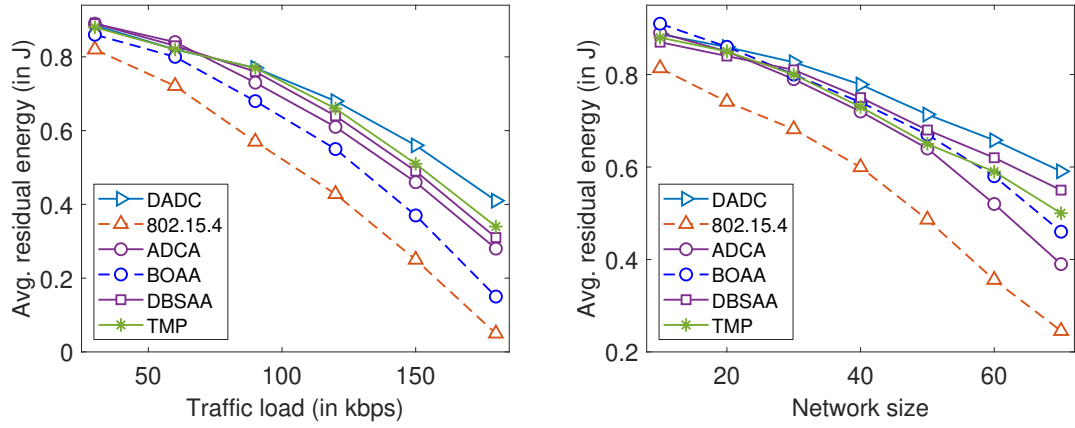
Parameters	Values
Frequency band	2.4 GHz
Maximum data rate	250 kbps
Number of nodes	71
Transmission radius	50 m
B0	8
S0	2
Initial Energy	1 J
Energy consumed to receive a frame	0.003 J
Energy consumed to transmit a frame	0.006 J
Energy consumed during sleep-state	0.000 030 J

clusters (Fig.2) is set up. The network topology is comprised of thirty-one coordinators and forty end-devices. The first coordinator to initiate the network is chosen as the PANC. A device is assigned the role of a coordinator to support association for other devices for extending the network size. End-devices do not facilitate further association of devices to itself. However, when such a need may arise, the end-device (assuming it as an FFD) requests its parent coordinator to upgrade its role to a coordinator. Such a request may be granted based upon available resources. These roles are assigned during network topology setup. Further, a child device associates with a parent coordinator (denoted by a parent-child link) only if they are in the transmission range of each other.

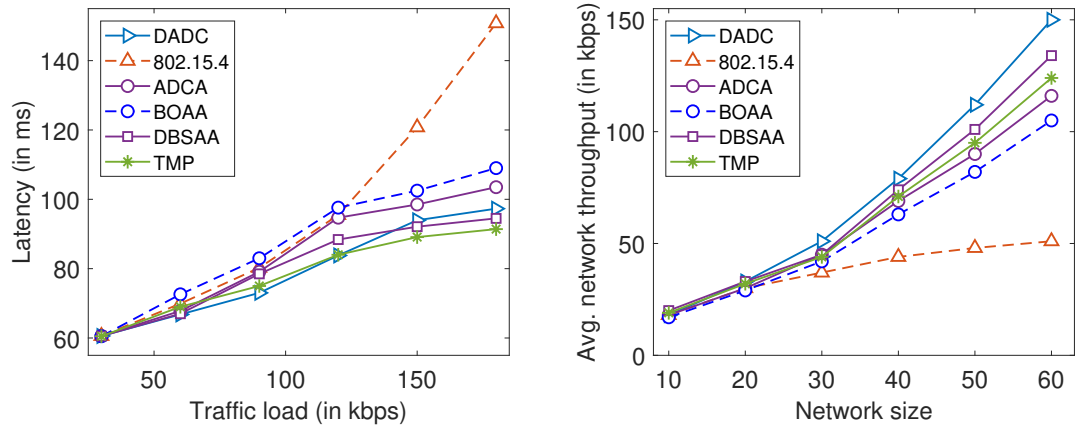
7.1.1 Performance measurement of DADC. We compare the performance of the proposed DADC algorithm with schemes like TMP [8], ADCA [45], BOAA [41] and DBSAA [42]. The authors in TMP and ADCA duty-cycle by adapting the S0 parameter keeping B0 fixed, whereas, in BOAA scheme, only the B0 parameter is adapted. Contrarily, in DBSAA mechanism, both the parameters are tuned.

Fig. 8a shows the average residual energy of the coordinators in the network for the proposed DADC mechanism along with TMP, ADCA, BOAA, DBSAA algorithms and IEEE 802.15.4, respectively. The traffic in the network is increased by generating more frames per BI by the devices. Networks based on IEEE 802.15.4 initially suffer from idle listening and later by high contention and transmission failure, leading to energy wastage. Devices in such networks exhaust their power and lose synchronization with a section of the network topology. TMP and DBSAA compute its duty-cycle based on the offered load, delay, and reliability constraints. These factors restrict selecting a smaller active period, suitable for networks with low-duty cycle requirements. BOAA is constrained with adapting only the B0 parameter, i.e., the beacon transmission frequency. The proposed DADC mechanism understands the contention in the channel efficiently than BOAA, ADCA and DBSAA schemes as the later schemes adapt based on sub-optimal measurements and predefined thresholds. Thus, the network topology operating DADC mechanism will have a 5-15% longer network-life.

Fig. 8b illustrates the residual energy of coordinators implementing various duty-cycling schemes. Network extension (up to 70 nodes) results in an increased number of data frames in the channel as well as channel contention. Duty-cycling schemes like TMP, ADCA, BOAA and DBSAA are suitable for small network topologies like star topology [8, 17]. These schemes do not function efficiently when the network size is increased. This is due to the limitations in determining superframe occupation ratio, collision ratio, queue size, and idle time in their respective schemes. These limitations are apparently visible when the network size is increased beyond 20-25 nodes. On the other hand, DADC relies on the MAC parameters that do not result in significant overhead among the coordinators and is suitable for large-scale network topologies.



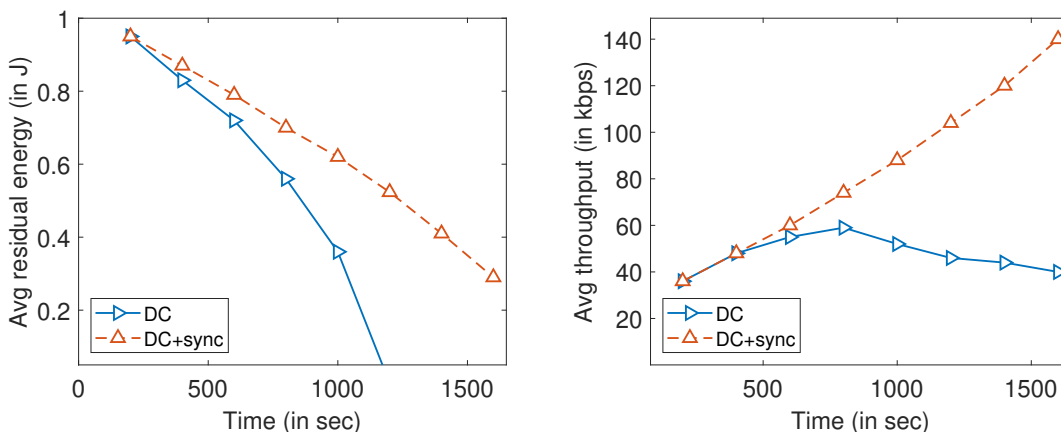
(a) Comparison of average remaining energy and network load. (b) Comparison of average remaining energy and network size.



(c) Comparison of network traffic and latency in transmission. (d) Comparison of network throughput and network size in transmission.

Fig. 8. Performance measurement of DADC.

Fig. 8c and Fig. 8d show the network reliability of the duty-cycling schemes in terms of delay and throughput. The variation in latency is observed to be minimal among the different schemes. TMP and DBSAA have the least latency as it is bounded by certain thresholds in delay, packet delivery, and SOR. TMP has strict latency requirements, as it is primarily based on medical applications. BOAA and ADCA thrive for low duty-cycle and higher reliability, respectively. Thus, frames generated during the inactive period wait longer before accessing the channel. Also, the increase in BE and retransmissions arising from collisions results in higher latency during transmissions. On the other hand, DADC focuses on balancing the duty-cycle as per channel traffic without any specific constraints in terms of delay, throughput, and energy consumption. The proposed scheme adjusts the superframe parameters to keep the latency within the optimal range.



(a) Residual energy of duty-cycling topology operating synchronization. (b) Throughput of duty-cycling topology operating synchronization.

Fig. 9. Performance of DADC in the presence of an operational synchronization scheme.

Fig. 8d illustrates that the network throughput linearly increases with the number of nodes in the network. If the active period is not increased to accommodate the increasing number of frames in the channel, the effective throughput of the network may fall. The DADC effectively estimates the increase in channel traffic, while other schemes, such as DBSAA [42], ADCA [45], and TMP [8] wait for the threshold value to be exceeded before adapting the superframe parameters. These above schemes rely on metrics like collision rate, the number of successfully received frames, and delay constraints to trigger the duty-cycling mechanism in the coordinator. As the network experiences a steady increase in throughput with the increase in data-generating nodes, the duty-cycling mechanism is not triggered. Basically, the duty-cycle is invoked with the increase in the channel contention resulting in longer delay compared to the threshold value. However, by then, the network is operating at a lower throughput than the potential throughput. Hence, DADC achieves about 5-15% higher throughput compared to the other related schemes.

7.1.2 Performance of DADC with/without synchronization. Initially, we evaluate our proposed mechanism in the presence and absence of an operational synchronization scheme. We compare the effectiveness of DADC mechanism based on residual energy and average throughput. The number of actively transmitting devices is gradually increased over time to realize the increase in channel traffic. Based on this, DADC adapts the B_0 and S_0 parameters accordingly. In the presence of a synchronization mechanism, DADC is able to reduce energy consumption through communication between associated devices about the updated B_0 and S_0 values. Also, the network is able to reduce the loss of frames (thereby increasing throughput) by recomputing the transmission offsets of the coordinators to avoid overlapping transmission periods. The neighboring coordinators have sequential transmission slots that can overlap with each other if any of the coordinators increase their respective S_0 . On the other hand, the absence of an operational synchronization mechanism results in loss of frames that require retransmission. Although the existence of a synchronization scheme has its own transmission overhead, however, the amount of energy consumed through its operation is considerably low compared to the energy drainage from collisions and channel wastage. Therefore, such a network has a longer network lifetime than a network without synchronization. The experimental observations are shown in Fig. 9a and Fig. 9b.

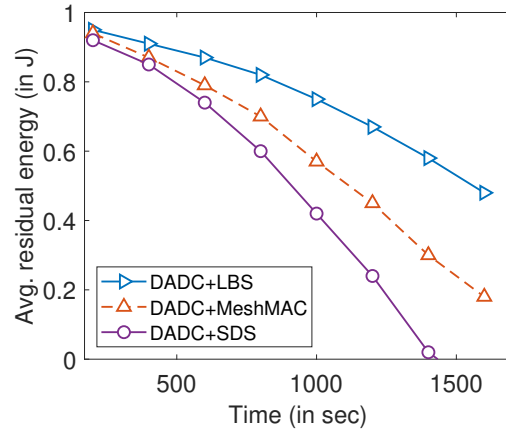
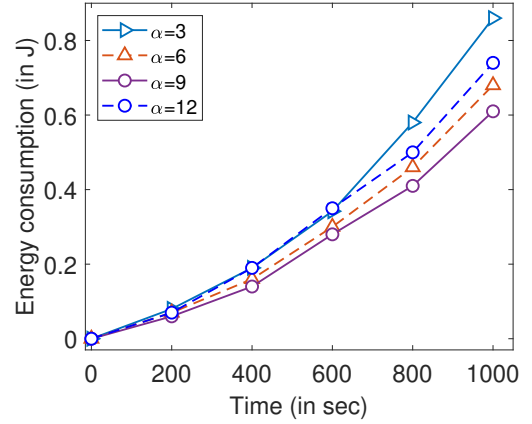


Fig. 10. Suitable synchronization scheme for DADC.

Fig. 11. Energy consumption with different α values for DADC.

As discussed earlier, duty-cycling schemes, including DADC, alter the B0 and S0 values of the coordinator to optimize their sleep period. As a consequence of the changes in the superframe parameter, the synchronization among the adjacent devices may be lost. This is due to the fact that synchronization schemes are based upon these superframe parameters. The loss in synchronization triggers recomputing of fresh non-overlapping transmission schedules. In other words, duty-cycling often results in loss of synchronization. This necessitates the need to address both issues together and not in isolation. However, previous work [8, 29, 35, 36, 41, 42, 44, 45] in this direction has largely ignored the inter-dependencies between these two schemes.

7.1.3 Evaluating an appropriate synchronization scheme for DADC. Next, we evaluate the performance of DADC alongside different synchronization schemes like SDS [32], MeshMAC [40] and LBS [15]. The objective of this experiment is to identify a suitable synchronization scheme that adds minimal overhead in terms of energy consumption. As the synchronization mechanism is frequently invoked upon duty-cycling, it is desirable to have low overhead during re-synchronization. Centralized schemes like SDS requires the PANC to recompute the transmission offsets of all the coordinators in the network. This is a very expensive operation for frequent duty-cycling networks. A distributed mechanism like MeshMAC reduces the energy expenditure for synchronization by keeping the overhead within the 2-hop neighborhood of the duty-cycled coordinator. MeshMAC assumes that the respective B0 and S0 parameter values to be equivalent throughout the network. Duty-cycling will violate this assumption. LBS, on the other hand, addresses the overhead incurred by the previous schemes by identifying the coordinators that need to adapt their transmission slots while other coordinators can continue using their existing schedule. Thus, we observe from Fig. 10, the combination of DADC and LBS are best suited for a cluster-tree based network topology.

As defined in the subsection 5.2, the value of α determines the frequency of operation of the DADC mechanism. Energy consumption during duty-cycling and corresponding LBS re-synchronization overhead is computed when α ranges between 3 to 12. A lower value of α implies frequent duty-cycling; however, it may not be optimal considering the number of re-synchronization it induces, leading to further energy consumption to stable the network. Contrarily, higher values of α mean longer intervals between successive attempts to duty-cycle. Nonetheless, this may introduce

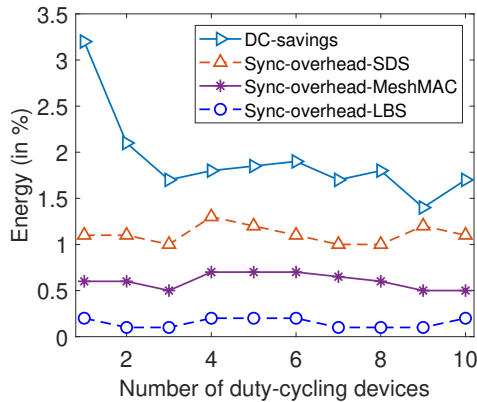


Fig. 12. Synchronization overhead alongside energy gain through duty-cycling.

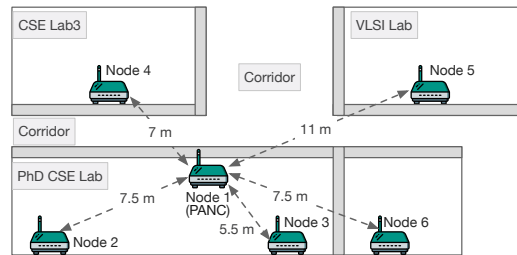


Fig. 13. Test bed setup.

temporary idle listening until duty-cycling is performed. Fig. 11 shows the energy consumption for the different α values considered. The value of α should be chosen based on the type and the needs of the network application.

7.1.4 Trade-off analysis of operating a synchronization scheme alongside a duty-cycling mechanism. We evaluate the energy savings through DADC, and the corresponding synchronization overhead (using SDS [32], MeshMAC [40], and LBS [15]) incurred. The objective of this experiment is to analyze the trade-off between duty-cycling and associated synchronization overhead. To determine the effective energy gain through duty-cycling, the synchronization overhead on the network has to be considered. The benefits of duty-cycling by a coordinator is outweighed if the associated synchronization overhead is higher than the corresponding energy savings through duty-cycling. Fig. 12 shows the energy savings in the network via duty-cycling (considering the duty-cycling overhead) and the associated overhead of different synchronization schemes. We observe that a centralized scheme like SDS incurs high overhead as the PANC collects the B0 and S0 parameters from all the coordinators in the network to compute a network-wide non-overlapping transmission schedule. The effective energy savings from duty-cycling are almost offset by high associated synchronization overhead. In MeshMAC, up to 2-hop neighbors of a duty-cycled coordinator exchange messages to recompute their respective transmission slots. Thus, the synchronization overhead is limited to the 2-hop neighbors. In contrast, the LBS mechanism minimizes the re-synchronization overhead by recomputing the transmission slots of only the effected coordinators instead of all the 2-hop neighbors. Therefore, it can be concluded that to maximize the energy savings, an effective re-synchronization mechanism needs to be operated alongside the duty-cycling scheme.

7.2 Implementation of DADC in a testbed setup

The proof-of-concept of the proposed duty-cycling scheme is validated with the help of a small testbed set-up that comprises of six Raspberry Pi (RPi-Model:3B) devices, each equipped with an Openlabs RPi 802.15.4 radio [6]. The aim of these experiments is to showcase the working of DADC when incorporated in to the IEEE 802.15.4 standard. It is worthwhile to note that the network size is scalable. We use the radio module (containing Atmel AT86RF233 chip-set) for an IEEE 802.15.4 compliant physical layer for transmissions. A battery as an external energy source is used to power the RPi. Moreover, DHT22 digital temperature and humidity sensors are used for sensing and data collection. The

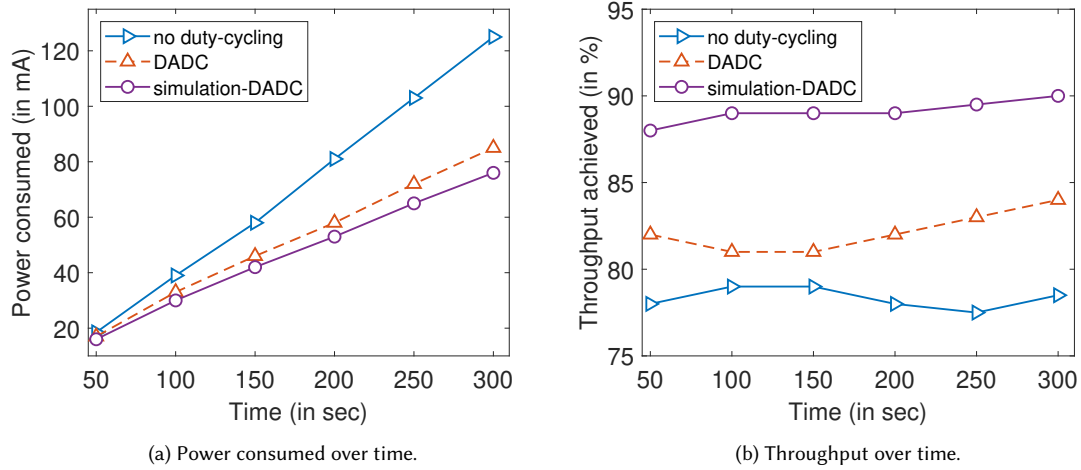


Fig. 14. Performance of DADC in a real testbed setup.

implementation is done using Linux wpan-tools. The primary objective is to showcase the energy savings resulting from employing the proposed scheme. The testbed is set up as shown in Fig. 13. Node 1 is 7.5 m away from Node 2 and Node 6. The respective distance between Node 1 with Node 3, Node 4 and Node 5 are 5.5 m, 7 m and 11 m. Traffic scenarios are taken from an IIoT scenario as in [9]. The superframe parameter B0 and S0 are set to 8 and 3, respectively. We record the observations from the experiments on 50 seconds time interval. The power consumption of the transceiver is available in the data-sheet [4]. Under a workload of 5 kbps, an average throughput of 4.1 kbps was achieved in a noisy and error-prone environment. Reducing idle listening and retransmission of data frames by dynamic and adaptive selection of B0 and S0 values resulted in increased energy savings in the network. Also, optimal active period ensured a higher throughput during varying channel traffic. Fig. 14a and Fig. 14b illustrate the network performance in terms of energy and throughput. Note that the simulation parameters for power consumption were considered according to the hardware parameters. The results obtained through both the set of experiments corroborate with our findings on higher energy savings and improved network performance by operating DADC with our proposed synchronization scheme. We observe a performance difference of around 3% between results obtained through testbed implementation and simulation. This is due to the interference from other operating networks during data transmission.

7.3 Discussion and Limitations of DADC

The proposed duty-cycling mechanism enhances the network lifetime, minimizes the duty-cycling overhead, and optimizes the network performance. The improvements of the proposed algorithm over existing schemes are summarized as follows.

- DADC adapts the superframe parameters based on the channel state that is reflected in MAC parameters BE , NB , and NR . The use of MAC parameters to estimate channel contention addresses the limitations of existing approaches [8, 29, 35, 36, 41, 42, 44, 45] that are based on either SOR or buffer/queue length.

- The proposed scheme does not define any new parameters; therefore, no additional overhead is incurred. In contrast, prior schemes define several parameters like SOR, collision ratio, queue/buffer occupancy, idle period, and transmission frequency to estimate channel state.
- The proposed mechanism can be invoked after a pre-defined set of BI to reduce network overhead. However, the existing schemes compute SOR, collision rate, and idle period at every BI that adds to the overhead.
- Finally, DADC does not rely on pre-defined threshold values for duty-cycling. This allows it to adjust to varying channel conditions dynamically. On the other hand, prior works are based on thresholds of SOR, collision ratio, delay, packet delivery, and buffer occupancy resulting in slower response (adapting the B0, S0 parameters) to channel traffic changes.

Few limitations of the proposed scheme exist. These are enumerated as follows.

- DADC uses the default values for MAC parameters as specified in the standard. The current values of *BE*, *NB*, and *NR* are compared against the default MAC values to adapt the B0, S0 parameters accordingly. The default values signify a channel state, to begin with, and this may result in higher network-time to reach an optimal duty-cycle. In such a scenario, a coordinator repeatedly performs duty-cycling to set the optimal B0, S0 values. For example, a higher value of *NB* (for instance *NB*=4) does not increase the active period of a coordinator when compared with the default value of *macMaxCSMABackoffs*. The S0 parameter is incremented when the value of *NB* reaches 5. However, with a lower value for *macMaxCSMABackoffs*, the S0 parameter can be incremented at *NB*=4 itself. Note that the proposed algorithm also considers other MAC parameters to identify changes in channel contention and adapt the superframe parameters accordingly.
- Similar to other duty-cycling schemes, DADC also affects the synchronization of the network as it alters the superframe parameters. The synchronization schemes' dependency on these superframe parameters in computing a transmission schedule results in a loss of synchronization after duty-cycling. An additional overhead in re-synchronizing the network is incurred. To minimize the overhead of re-synchronization, specific algorithms need to be designed to lower such associated costs. This is possible by identifying coordinators that need to recompute their schedule or shift their existing transmission slots while the other coordinators use their existing transmission offset.

8 CONCLUSION

In this paper, we first highlight the limitations of existing duty-cycling schemes designed for IEEE 802.15.4 based cluster-tree networks. Then, we estimate the delay and energy consumption during frame transmission using a Markov model. We analytically compute the energy spent on idle listening, which can be accounted for through duty-cycling in a synchronized network. Later, we propose a duty-cycling mechanism named DADC that dynamically adapts superframe parameters (B0, S0) based on channel conditions, to ensure optimal duty cycles. This is done with the help of MAC parameters *macMaxBE*, *macMinBE*, *macMaxCSMABackoffs*, and *macMaxFrameRetries* that reflect the current channel conditions. The proposed mechanism does not define any new parameters and therefore adds no additional overhead. Through experimental analysis, we show that the network performance is optimal when the proposed mechanism operates alongside a synchronization scheme.

As duty-cycling affects synchronization of the network by adapting superframe parameters, we further aim for quick convergence of the duty-cycling mechanism to a synchronized beacon schedule. This will reduce the associated overhead of re-synchronization. Future work will include DADC implementation on complex testbed setup. In addition,

we intend to analyze dynamic slot allocations to an existing transmission schedule for IEEE 802.15.4e based TSCH and DSME MAC behaviors. Such a duty-cycling mechanism will support schedule formation based on traffic flow constraints and QoS requirements of various applications in multi-channel network topologies.

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