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# Duty cycle learning algorithm (DCLA) for IEEE 802.15.4 beacon-enabled wireless sensor networks

Rodolfo de Paz Alberola *, Dirk Pesch

*Nimbus Centre for Embedded Systems Research, Cork Institute of Technology, Rossa Avenue, Cork, Ireland*

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ABSTRACT

The current specification of the IEEE 802.15.4 standard for beacon-enabled wireless sensor networks does not define how the fraction of the time that wireless nodes are active, known as the duty cycle, needs to be configured in order to achieve the optimal network performance in all traffic conditions. The work presented here proposes a duty cycle learning algorithm (DCLA) that adapts the duty cycle during run time without the need of human intervention in order to minimise power consumption while balancing probability of successful data delivery and delay constraints of the application. Running on coordinator devices, DCLA collects network statistics during each active duration to estimate the incoming traffic. Then, at each beacon interval uses the reinforcement learning (RL) framework as the method for learning the best duty cycle. Our approach eliminates the necessity for manually (re-)configuring the nodes duty cycle for the specific requirements of each network deployment. This presents the advantage of greatly reducing the time and cost of the wireless sensor network deployment, operation and management phases. DCLA has low memory and processing requirements making it suitable for typical wireless sensor platforms. Simulations show that DCLA achieves the best overall performance for either constant and event-based traffic when compared with existing IEEE 802.15.4 duty cycle adaptation schemes.

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## 1. Introduction

Wireless sensor network (WSN) nodes are usually battery operated and, in many deployments, replacing or recharging their batteries is costly or even infeasible. Consequently, low power operation is considered a primary requirement for WSN communication protocols. Specifically, the idle listening problem must be solved as it has been identified as one of the major sources of energy wastage [1]. This occurs when the nodes are unaware of when data traffic is generated by other nodes and their transceiver continuously stays in the receiving mode even when there is no data traffic for them.

The IEEE 802.15.4 standard [2], which is currently the most widely adopted MAC protocol, defines several type of nodes that take different roles during the operational phase of the system. Full function devices (FFD), also called beacon enabled devices, can operate either as Personal Area Network Coordinators (PANc), Cluster Heads (CLH) or routers. On the other hand, reduced function devices (RFD) also called non beacon devices can only operate as end devices. FFDs can generate, receive and/or forward data frames whereas RFD have reduced functionalities only using its radio to receive control information and send collected data. End devices may therefore be asleep unless they have data to transmit or receive control commands. This work considers that FFDs are battery powered and act as the Cluster Head forming a star of end devices collecting data around it. In this scenario, as the FFDs cannot predict when other sensor nodes are going to send their

* Corresponding author.
*E-mail addresses:* rodolfo.depaz@cit.ie (R. de Paz Alberola), dirk.pesch@cit.ie (D. Pesch).

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data to them, they need to be always awake to receive all the information collected, which rapidly depletes their batteries. To overcome this problem, the standard specification defines the beacon enabled mode. This mode supports the transmission of beacon frames from coordinator to end devices allowing node synchronization. Synchronization allows all devices to sleep between coordinated transmissions which contributes to reduce idle listening, resulting in prolonged network lifetimes.

The beacon mode employs the superframe structure depicted in Fig. 1. Its format is established by the coordinator and is defined by two parameters, the beacon interval (BI), which determines the time between two consecutive beacon frames, and the superframe duration (SD), which determines the nodes' active period in the BI. The superframe duration is composed of a contention access period (CAP) in which all devices use a slotted CSMA/CA protocol to gain access and compete for time slots, followed by a contention free period (CFP) for low latency applications which is divided into guaranteed time slots (GTSs). In order to reduce energy consumption, the coordinator may introduce an inactive period by choosing BI > SD. The inactive period defines a time period during which all devices, coordinator included, go into a sleep mode. BI and SD are determined by two parameters, the beacon order (BO) and the superframe order (SO), respectively, as per Eq. (1) where aBaseSuperframeDuration = 15.36 ms (assuming 250 kbps in the 2.4 GHz frequency band) denotes the minimum duration of the superframe, corresponding to SO = 0.

$$\left.\begin{aligned} \mathrm{BI} &= aBaseSuperframeDuration \cdot 2^{\mathrm{BO}} \\ \mathrm{SD} &= aBaseSuperframeDuration \cdot 2^{\mathrm{SO}} \end{aligned}\right\} for\ 0 \leqslant \mathrm{SO} \leqslant \mathrm{BO} \leqslant 14. \quad (1)$$

Although the beacon-mode was developed with limited power supply availability in mind by allowing the introduction of sleep periods, it does not specify how the duration of active and sleep periods can be adapted based on the traffic generated by end devices. Setting the duty cycle is however a major requirement in order to achieve a good balance among network reliability and power consumption. Thus, the physical implementation of this MAC protocol requires additional power management considerations that are not defined in the standard. Specifically, the coordinator needs to control the duty cycle (DC), defined as the fraction of the time nodes are active, in order to provide energy efficiency. This time can be computed as the ratio between the superframe duration and the beacon interval that can be related to BO and SO as per the following equation:

$$DC = \frac{\mathrm{SD}}{\mathrm{BI}} = 2^{\mathrm{SO}-\mathrm{BO}}. \quad (2)$$

The smaller the duty cycle the lower is the energy consumption. However, due to the inherent resource constrictions of sensor nodes, a small duty cycle can cause buffer overflows and delays. On the other hand, although a high duty cycle enables end devices to transmit a higher number of data frames and decrease delay it may also increase the time the coordinator spends in idle listening. Consequently, duty cycle adaptation is necessary to enhance the performance of IEEE 802.15.4 beacon-enabled networks and it is therefore the main objective of this work.

A number of reports in the literature present work aiming at adjusting the duty cycle to the traffic load using the IEEE 802.15.4 beacon-enabled MAC. However, as discussed in Section 2, these works have limitations when applying them to diverse event-based, periodic or spatial traffic distributions. We therefore propose in this paper a duty cycle learning adaptation algorithm (DCLA) for IEEE 802.15.4 beacon-enabled networks that overcomes their limitations.

## 2. Related research efforts

Several approaches have been developed for the IEEE 802.15.4 standard towards adjusting node's duty cycle to the traffic changes using the beacon-enabled MAC. The earliest work on 802.15.4 duty cycle adaptation is known as the Beacon Order Adaptation Algorithm (BOAA) [3]. For the traffic estimation, BOAA uses the number of messages received from the end devices in order to estimate the network offered load. The authors propose to store the number of received messages from all devices during a number of beacon intervals in a buffer matrix. The proposed buffer matrix presents the advantage of giving some memory to the algorithm. This matrix however is not scalable for large networks as the number of rows increases with the number of end devices in the topology.

Alternatively, Jeon et. al. employ in their duty cycle algorithm (DCA) [4] additional information such as transmit queue occupation and end-to-end delay to select the duty cycle. In order to gather these statistics from end devices, they modify the reserved frame control field present in the MAC frame header so that no extra overhead is incurred. The queue occupation is computed as the average of a queue

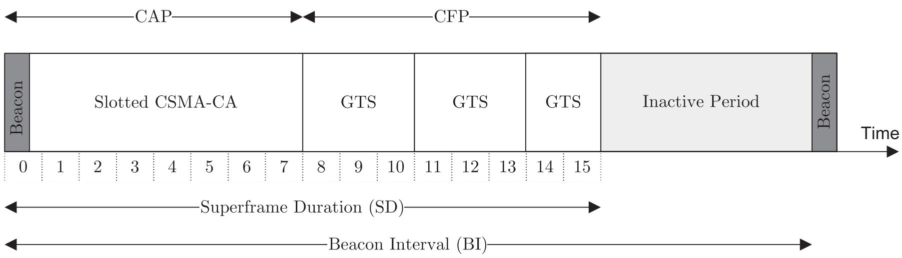


**Fig. 1.** The superframe structure of the IEEE 802.15.4 beacon-enabled mode.

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