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An Enhancements on IEEE802.15.4 Protocol's Sleeping Schedule with B-MAC Integration

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***Abstract*:** Energy consumption has become one of the most critical challenges facing the Wireless Personal Area Networks (WPAN) with the IEEE 802.15.4 beacon-enabled mode protocol. Since part of the challenge is to uncover the current standard for IEEE 802.15.4 protocol un-explanation of the technique for active and sleep cycle that might be applied in order to achieve higher and optimal network performance. This paper proposes an energy-efficient scheme to be implemented by combine IEEE802.15.4 MAC with Berkeley MAC (B-MAC). The combination aims to coordinate sleep schedules without using low power listening (LPL) approaches. The proposed algorithm is simply achieved without a need to add new steps in the IEEE 802.15.4 specification neither need to perform any additional functions. Evaluation results proved the proposed algorithm significantly outperforms the WPAN IEEE 802.15.4 standard in terms of Interference computation count, throughput and residual energy capacity.

***Keywords*:** IEEE802.15.4, low rate wireless personal area networks (LR-WPAN), sleep cycle, B-MAC, energy, throughput, wireless sensor networks (WSN).

1. Introduction

With the recent technological advances in Wireless Sensor Network (WSN) and the increasing popularity of low rate Wireless Personal Area Networks, IEEE802.15.4 protocol is considered as one of the most prominent and widely used protocols in the military, environment monitoring, and Medical applications [1]. Specifically, the IEEE 802.15.4 standard specification covers the physical layer and Medium Access Control (MAC) sub-layers. Several WSN platforms have been developed, for example, ZigBee [2] or LoWPAN [3]. Which are compatible with specifications of the IEEE802.15.4 standard and rested on top of 802.15.4 link layer for complete the protocol stack. This stack is fulfilling the market requirements for low-data-rate, low-cost and operate on low battery power and little infrastructure [4]. The critical and challenging problem of IEEE802.15.4 beacon-enabled networks is how to reduce energy consumption and achieve high performance. Most of the available studies in this scope concentrate on modification of the superframe order (SO) and beacon order (BO). Those are special parameters of the IEEE 802.15.4 frame with related to organize the active and inactive periods. In light of this, the purpose of this paper is to focus on the sleep schedule after the transmission packet without adjustment for IEEE802.15.4 parameters. The structure of the paper is as follows. An overview about IEEE802.15.4 and B-MAC are given in Section II. The literature review will be discussed in Section III. Our algorithms are described in detail in Section IV as a problem formulation. Section V describes some performance evaluations. Finally, section VI is devoted to the conclusions of this paper, with future work.

2. Overview of the Used Protocols

2.1 IEEE 802.15.4 Standard

IEEE802.15.4 is suitable for low data rate communication over limited power wireless devices. The protocol can operate in a star network topology where all transactions are performed between one central controller named PAN coordinator, or in peer-to-peer topology where every device in the network can directly communicate with others whereas the central PAN coordinator works as cluster management [2]. IEEE802.15.4 standard defines two different device types either FFD or RFD based on their function. An FFD can operate as the PAN coordinator, able to perform energy detection (ED) and active scans. Whereas RFD is only allowed to communicate with a single coordinator. Also, it can be implemented using minimal resources of memory capacity and consume less power.

The more advanced features offered by the IEEE802.15.4 protocol has two kinds of operational modes; beacon-enabled and non-beacon-enabled. During non-beacon enabled mode, the PAN coordinator does not transmit beacons. This mode is appropriate for light traffic loads among the network devices. The access to channel and exchange data frame is executed through unslotted CSMA/CA mechanism, as well as, network life or battery life of nodes is longer than life in the beacon-enabled network since to in a non-beacon network, the nodes wake up less frequently. On the beacon-enabled mode, the PAN coordinator sends beacon periodically to identify its PAN ID to be synchronized with associated nodes as illustrated PAN superframe structure. In fact, in a beacon-enabled network, the nodes consume more energy because all nodes in the network shall be wake up on a regular time (called beacon interval) and resynchronize their timer. This leads to less battery life of nodes than the non-beacon-enabled. In addition, Medium access contention is based on slotted CSMA/CA.

Figure 1 shows The IEEE802.15.4 superframe structure. At the first slot, each PAN coordinator transmits beacon frames periodically which holds the information about network synchronization and some details such as duration, list of pending messages, GTS devices address, etc. Once the end device receives the beacon, it resynchronizes its timer with sleep/wake scheduling and begins the inactive period. Each superframe structure comprises two periods namely active and the optional inactive. During the inactive period, the device must switch OFF their radio transceiver to conserve energy. The second section is the active period, also called the superframe duration (SD), specifically partitioned into 16 equal size slots comprises of three stages: beacon, contention access period (CAP), and contention-free period (CFP).

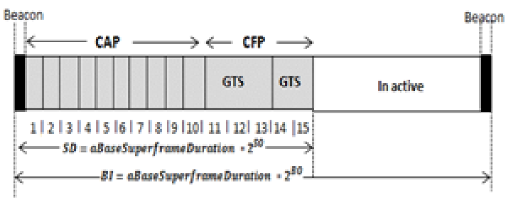

Figure 1. IEEE802.15.4 Superframe Structure

In a beacon-enabled network with superframes, as shown in figure 1, the time duration of the whole structure of the superframe and its active period is determined by two main parameters, the Beacon Order (BO) and the Superframe Order (SO). The parameter BO defines the length of the superperframe including both an active and inactive period (also called beacon interval, BI), which can be obtained by Equation 1. While the parameter SO defines the length of the active period mainly partitioned into two parts that are CAP and CFP period (also called superframe duration, SD), which can be obtained by Equation 2. Furthermore, let us denote Tslot to be the time for one timeslot, which can be obtained by Equation Eq. (3).

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

$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (2)$$

$$T_{slot} = aBaseSlotDuration \times 2^{so} \quad (3)$$

where $0 \leq SO \leq BO \leq 14$

Where *aBaseSuperframeDuration* and *aBaseSlotDuration* are a constant value and predetermined by the definition of standard as 960 and 60 symbols and indicate to the minimum duration of superframe and timeslot, respectively. Taking into consideration that, in case SO value equivalent to BO value, which means BI length is exactly equal to the SD length, that means which indicates that there is no inactive portion.

2.2 Berkeley MAC

B-MAC, also known as Low Power Listening, is considered as one of the most common protocols for wireless sensor networks. A major advantage of working with this protocol is by default, it neither uses RTS/CTS nor ACK control frames as well as, does not require any synchronization. It allows a sensor (RFD) to periodically listening for channel activity.In brief, the B-MAC protocol works as follows: if sensors do not have any packet to transmit or a channel state is idle, sensors switch OFF their receivers for a relatively long interval of time and waking it up at regular intervals to listen to channel state and check for ongoing transmissions. Otherwise, if devices found the channel is busy during the channel sensing process, the nodes turn ON their receivers until receiving data packet or after a certain time out period [5]. The B-MAC transmission procedures can be summarized as if the sender device wishes to send the packet to PAN coordinator or neighbors, it shall first send a short packet called preamble segment which has a tiny bit longer than the check time duration of the receiver. when the receiver detects a preamble, it is staying awake until receiving the whole preamble. After transmitting preamble, the sender node sends the actual data packet and then returns to the sleep state. Figure 2 shows the finite state machine of B-MAC.

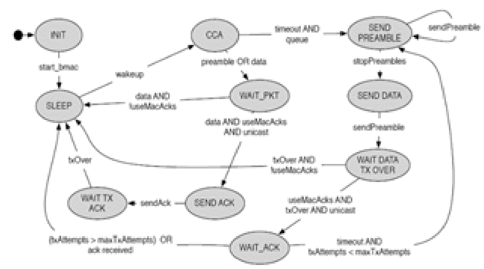

Figure 2. Finite state machine of B-MAC [5]

3. Literature Review

The BO and SO parameters determine the duty cycle by which they are controlling the sleep/wake-up states in the attached radio. In this context, three possible cases are classified as our approaches to managing the node's lifetime based on SO and BO parameters. The first possibility is setting both BO and SO related values based on the remaining (residual) energy level of a node battery. The second one is adjusting the SO value while the BO value is fixed. The last one is adjusting the BO value and setting the SO value as fixed In [6] the authors proposed a method such as the first step the nodes compute its energy consumption, then send their current energy levels to the PAN coordinator. If it discovers that a node has insufficient remaining energy, the PAN coordinator modifies its present duty cycle through resetting both parameters BO and SO. In [7] authors proposed an adaptive MAC for efficient low power communications, named AMPE. The proposed real algorithm shows a change of the duty cycle at each node according to superframe occupation measurement, where the value of SO can be larger when traffic load estimation was greater than a fixed threshold. Otherwise, the SO could be small equal value. Whereas the value of BO fixed and equal to BOmax. In [8] the authors proposed the Dynamic Superframe Adjustment Algorithm (DSAA). The algorithm works only to modify the SO whereas BO is fixed. The PAN coordinator is modifying the length of the superframe duration (active period) depends upon the comparison of the ratio of collision and the superframe occupation with specific thresholds.

The authors in [9] determined the superframe duration length (Active period) and CSMA Backoff Exponent (BE) value based on the load traffic of the entire network. In [10] the authors proposed an Adaptive algorithm to optimize the dynamics (AAOD). That uses a very simple algorithm. It allows the coordinator to increase SO based on the number of received packets in each superframe. In [11] the authors considered the managing mobility in cluster tree topology based on a LQIthreshold value, they proposed an energy-efficient implementation by managing the mobility in the networks using the speculative algorithm.

Based on our best knowledge, most of the studies did not consider the high energy consumption and satisfy QoS requirements at the same time under irregular load conditions. Notably, the manipulation of SO and BO parameters by coordinator led to a lower duty cycle, which means all nodes may spend most of their time in a sleep mode. This will increase both, latency and collision rate since of the small access opportunities among nodes.

4. Problem Formulation

The main idea of the proposed model is how the sleeping and wake-up states can be organized among nodes to prevent/reduce the beacon collision occurrences of data or control frames. This with the assumption of the beacon-enabled mode approach in the star network topology. Also, in our work, we ignore the process of checking the channel using LPL, since we consider star network where PAN coordinator is managing all transactions with transmitting buffered data mechanisms to associate nodes in PAN coordinator.

Our main strategy is to enforce the sensor nodes to wakeup (i.e., switching ON the transceiver) when the following three cases have occurred: receiving a beacon frame from the coordinator, using its allocated GTSs slot in CFP, and the node has a packet to send. The finite state machine of our algorithm illustrated that in Figure 3. Receiving a beacon frame could happen when the first beacon is received. At this point, each node is scheduling a new wakeup timer to receive the next beacon according to the information of the superframe's structure that exists in the beacon. According to that, each node checks if its address is announced in the listed GTS allocation and pending message address, respectively. If it is presented in the listed GTS allocation, it will schedule a new wakeup timer corresponding to its allocated time slot. Moreover, it sends the MAC command requesting the data and enables its receiver for the maximum duration of [aMaxFrameResponseTime] to receive completely the buffered data. On the other hand, if its address was in the pending message address list, the node will back to the sleeping state when pending data is successfully received or when [aMaxFrameResponseTime] interval has a timeout.

In addition, the FSM shows clearly that, once a node has allocated GTSs slot in CFP, it wakeup and enable its transceiver in order to send/receive its packet without using the contention mechanism, after that, it goes back to a sleep state until next beacon. In addition, the FSM shows the last case, when the node receives send-request-primitive from the upper layer, it turns its transverse ON and contends for the medium using a slotted CSMA/CA to send its data packet, after that, it goes back to sleep state. The above description of our proposed schema is elaborated below as pseudo-code in Table 1.

Algorithm 1: GTS sleep/wake-up scheme

```
Input: BO, SO
Initialization:
Beacon Received
    • Schedule new wakeup timer for next beacon.

if (Beacon did not announce the device address) then
    Turn OFF transceivers.
else
    if (the address present in allocation List) then
        Schedule new wakeup timer in CAP.

    if (the address present in pending message List) then
        Send request command to poll pending data.
        if (use ACK && ACK has arrived && PF ==1) then
            Still awake until aMaxFrameResponseTime
            if (Pending msg received && use ACK) then
                Send ACK
            else
                Turn OFF transceivers.

if (send queue not empty) then
    Turn ON its transceivers & transmit packet
    if (use ACK && ACK has not arrived && retry limit not reached) then
        Retransmission packet
    else
        Turn OFF transceivers.
```

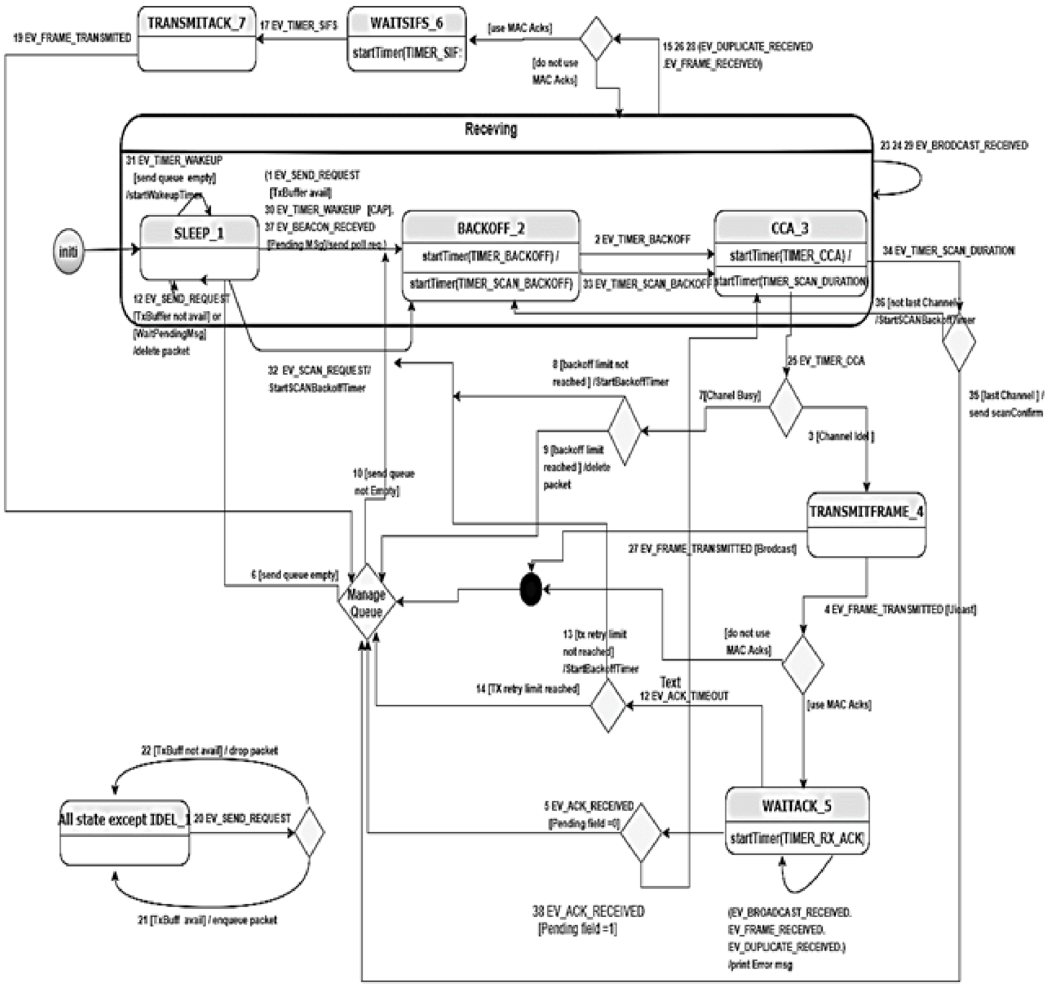

Figure 3. Finite state machine of sensor

5. Performance Evaluation

For the purpose of the performance evaluation of our algorithm, our simulation results were compared to IEEE802.15.4 Standard. Also, we simulate our algorithm through the OMNET++ simulator as the most widely used in the scientific community. OMNET++/INET is an open-source library parallel discrete event [12].

In detail, we consider star network topology, consist of 20 end devices and one PAN coordinator which are deployed in an area of 400×400 m. The sensor nodes are randomly deployed in the network, where the coverage range $R = 10$m. We consider the different values of SO and BI, where SO=BI =2,3,4,5,6 order to analyze the performance. Our simulation parameters and their value are mentioned in table 1. All experiments result in this paper show that our proposed schema outperforms the original standard in terms of interference count, residual energy capacity, and throughput.

Figure 4 illustrates the interference computation count concerning the superframe order, which occurs when multiple nodes are using the same radio frequency to send its packet in a wireless network link. The x-axis represents the length of the superframe and the y-axis represents the interference competition count. It can be observed that our proposed schema minimizes the interference by about 18% when SO=2 and this percentage increases with the increase of the length of the superframe reach up to 30% at SO=6.

Table 1. Simulation parameters

Parameters	Value
Bitrate	250 Kpbs
useMACAcks	True
BO=SO	2,3,4,5
BEmin	3
BEMAX	5
PWRtx	100mw
PWRrx	10mw
PWRidle	3mw
PWRbusy	5mw

Also, Interference reduction leads to minimizing collision rate and retransmission, which reflects on energy consumption. Figure 5 shows the residual energy capacity achieved using our proposed schema comparing with the standard. It can be observed that our proposed schema outperformed the original standard, especially when a long superframe. For instance, at SO=4 the capacity of residual energy conserved by approximately 10%, where increases of up to 29% in the

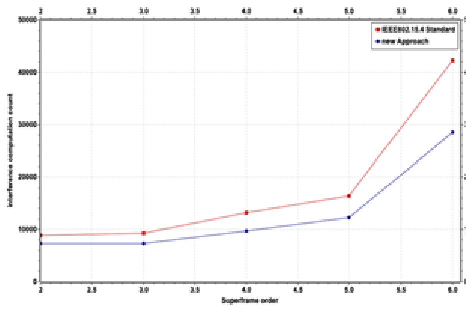

Figure 4. Interference computation count

percentage when SO=6.

The results in Figure 6 show the network throughput with respect to the superframe order from the coordinator point of view. It is obviously showing that our new approach has the highest throughput efficiency compared with the standard protocol. Clearly, the results showed that our proposed schema achieved almost similar performance in throughput at SO=2 and progressively increasing as the superframe order increased to reach up to 30% enhanced at SO=6.

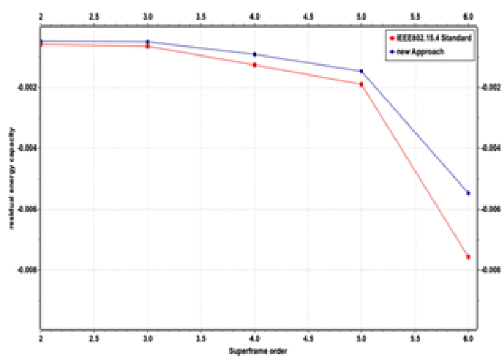

Figure 5. Residual energy capacity

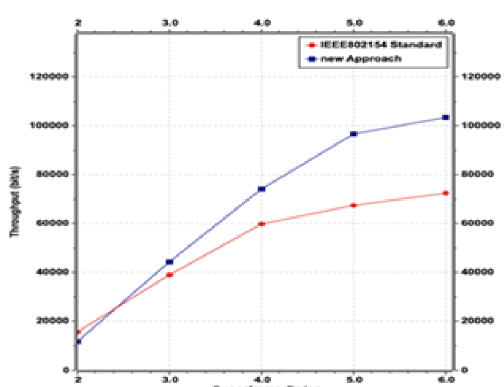

Figure 6. Network throughput

6. Conclusions and Future Work

The IEEE802.15.4 standard for LR-WPANs still requires more improvements to be an effective protocol in emerging applications such as environmental control and monitoring. In this paper, we have proposed a new approach for sleep /wake-up schedule in IEEE 802.15.4 networks. Our proposed approach allows the end-devices nodes to switch OFF its transceivers for a proportionally long time while it can be awaked in two cases; either when a node has a packet to send to the PAN coordinator or after poll the coordinator to receive the buffered packet. Our proposed algorithm was evaluated. Many experimental had been run and the results show that the new proposed scheme not only enhanced the overall network's throughput, concerning the IEEE 802.15.4 standard, but it also extended the network lifetime through the residual energy on battery allocates a significantly large number of associated devices. These are considered as performance enhancements that can be added into account for modifications.

The future can be planed as more sleep /wake-up scheduling to be investigated which more enhancements can be achieved. Also, we plan to extend our work to consider peer-to-peer topologies, take into consideration the low power listening (LPL) approach and investigate the performance improvements.

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