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Review of Energy Conservation Using Duty Cycling Schemes for IEEE 802.15.4 Wireless Sensor Network (WSN)

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Abstract Energy conservation is one of the crucial issues in wireless sensor network (WSN). A significant solution to conserve energy is done by deploying duty cycle management mechanisms in the WSN applications. This paper reviews several duty cycle mechanisms in WSN such as Duty Cycle Learning Algorithm, adaptive media access control (MAC) protocol for efficient IEEE 802.15.4 (AMPE), distributed duty cycle management (DDCM), distributed duty cycle management low power broadcast (DDCM + LPB) and distributed beacon only period. These mechanisms change their parameters such as idle listening, packet accumulation and delay in the end device transmitting queue to improve the energy conservation in WSN. The performances of these different energy conservation mechanisms have been compared at the MAC layer of IEEE 802.15.4 standard. It is found that the DDCM + LPB has made approximately 100 % enhancement in terms of average energy efficiency as compared to the other mechanisms. DDCM + LPB has significant enhancements by adapting the duty cycle according to the network traffic load condition. Using this mechanism, the duty

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cycle is increased when the traffic load increases and vice versa. Its energy efficiency also outperforms the conventional DDCM by the average of 10 %.

Keywords IEEE 802.15.4 standard · WSN · Duty cycle management · Energy efficiency

1 Introduction

The advent of the wireless sensor network (WSN), which is low power, self configuring, self healing, flexible, secure, and most importantly, consist of low cost device has been widely adopted in many application domains [1]. A WSN function could act as an enabler to collect the physical data, interface with the sensor node, and transmitting via a radio module to the base station. It could be configured as a "single hop", whereby the sensor node directly transmits the data to the base station, or in a "multi hop" configuration, whereby the node acts as a router, by relaying the information to the other nodes. WSNs have been deployed for several monitoring applications including military [2], environmental [3], health [4], home [5], agriculture [6], aquaculture [7] and slope monitoring [8].

In WSN monitoring system, the sensor node is fixed at the place of interest for long duration to gather the surrounding information. In some cases, the duration could be up to a year without any maintenance, and thus require efficient power consumption. Figure 1 shows the block diagram of sensor node consists of few cores including sensory, computational and communication.

The energy optimization could be done at different parts. In the specific case of the communication core, the energy consumption could be reduced by having optimum duty cycle mechanism [1,6].

The IEEE 802.15.4 is a part of IEEE family standards for physical and link layers meant to wireless personal area networks (WPANs). 802.15.4 operates either in a beacon-enabled or a non-beacon-enabled mode [9]. IEEE 802.15.4 media access control (MAC) defines several types of nodes that take different roles during the operational phases [10]. The MAC's duty cycles have been discussed primarily to increase energy conservation of sensor nodes, since it operates on a limited energy source. It could be scheduled into synchronous or asynchronous protocols according to the time synchronization condition [11].

Duty cycle is one of the most commonly used approaches to reduce the energy consumption during waiting time. Furthermore, it is one of the major sources of energy waste [12]. The

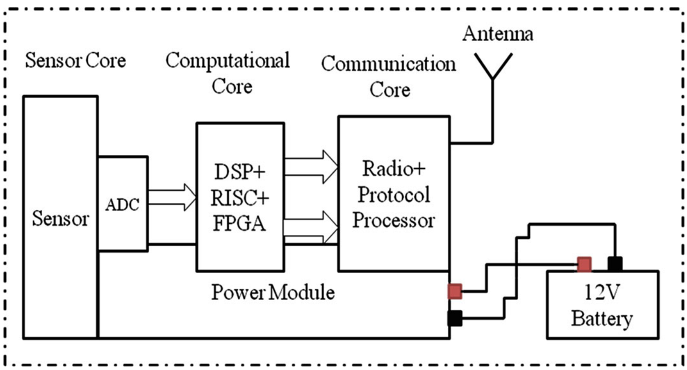

Fig. 1 Block diagram of the sensor node cores

function of duty cycle is to set unused communication interface of sensor nodes in low power or in the sleep mode for most of the time, and only wake them up regularly to save a large amount of energy [12–14]. In WSN, sensor nodes have to carry out sensing duties for a long period. The ratio of time, μ during which a sensor is awake is called duty cycle. Most of the applications, batteries cannot be replaced. From this point of view, the performance of WSN can be measured from the energy conservation or power control. In order to prolong the network lifetime, it is essential to reduce the switching frequency since the transition between active and dormant states, and it is cost time and energy to change from mode to another [13,15].

This paper reviews and compares several duty cycle management mechanisms at MAC layer for IEEE 802.15.4. These algorithms have been proposed by several authors to reduce the energy consumption related to the traffic load. The popular duty cycle mechanisms are including Duty Cycle Learning Algorithm (DCLA) [10], adaptive MAC protocol for efficient IEEE 802.15.4 (AMPE) [16], distributed duty cycle management (DDCM) [17], distributed duty cycle management low power broadcast (DDCM + LPB) [17] and distributed beacon only period (DBOP) [18].

In DCLA mechanism, its duty cycle changes based on idle listening, packet accumulation and delay in the end device transmitting queue. Meanwhile, in AMPE mechanism, the duty cycle is properly selected based on the load factor and superframe order (SO) parameter. The structure of DDCM is distributed between beacon interval (BI) and extra superframe duration (ESD) which adapt to traffic load condition and much faster by changing the duty cycle. The extension of DDCM which is DDCM + LPB further enhances DDCM by optimizing the node's energy consumption through low power beacon. The last mechanism which will be reviewed is DBOP that changes the duty cycle through beacon order period length (BOPL).

The paper is organized as follows. Sections 2 and 3 provide the overview of WSN and its energy conservation respectively. Section 4 presents the duty cycle mechanisms in WSN. The performance comparison of duty cycle mechanisms towards energy conservation is discussed in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 Overview of Wireless Sensor Network (WSN)

WSN is an abbreviation for wireless sensor network (WSN) which consists of a connected sensor devices and distributed within an area to sense or observe several parameters. Amongst parameters include motion, vibration, pressure and pollutions [19]. WSN has been seen in a widespread propagation of applications in the world, with concentration in investigation and manufacturing. The well-organized shape of technology usage of WSN does not depend on structures or regulations for a particular standard. This statement makes WSN important resources and attractive field for investigator. There are a lot of applications of WSN such communication devices and networks such as military side, indoor and outdoor fire war systems, healthiness monitoring, ecological applications, security applications, farming, weather changes, air pollution monitoring, landslide revealing, greenhouse monitoring, data logging, machine health monitoring, and studying animal actions [20].

The most important features and characteristics of WSN are extremely dispersed networks of tiny, lightweight wireless nodes, ease of use, and deployed in large statistics. Furthermore, it can observe the situation or scheme using the measurement of physical parameters such as high temperature, humidity, sound, vibration, and pressure [21]. The design of a WSN system is recommended to consider some factors such as fault tolerance (reliability), hardware constraints, scalability, product cost, and power consumption.

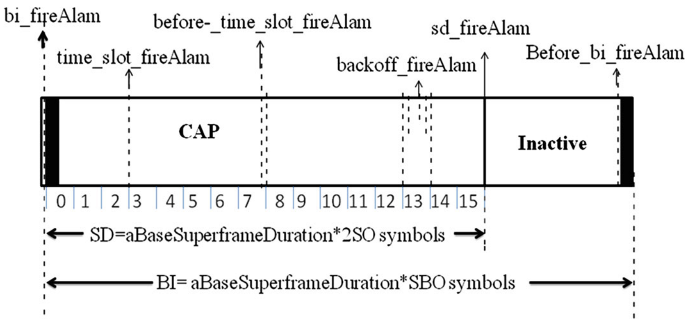

Fig. 2 Superframe management structure

The main features of WSN are power consumption, device processing speed, memory capacity and network bandwidth. WSN is a technology that enables a self configuring, low price, and completely customizable solution. Most of the WSN technologies are established by adapting IEEE 802.15.4 standard which are using different frequencies and protocols. Figure 2 shows the IEEE 802.15.4 superframe operation with active and inactive interval. The superframe structure composes of sixteen equal-length slots, which are divided into an active and inactive parts defined by the coordinator.

The functions of MAC layer are generating beacon frames if the device is a coordinator, which employing the carrier sense multiple access with collision avoidance (CSMA-CA) mechanism for channel access [22]. Many topologies of WSN evolve from a simple star network to a highly developed multi-hop wireless mesh network with a complex routing algorithm. One of the most commonly used standards in WSN communications is ZigBee IEEE 802.15.4 [23–25].

3 Energy Conservation in WSN

The recommended sensor node should operate at low power and could last long enough during the monitoring duration. Energy optimization could be done at various hardware levels, as has been discussed briefly in Fig. 1 [8]. At sensory core, the optimized energy utilization could be achieved by having efficient circuit design whereby the sensor will only be powered at specific time for data gathering process. After the process, the sensory core will go to sleep mode until the next round of data collection.

Efficient hardware for low power operation require integration and isolation, selectable power states (off, sleep, standby), operate at low voltages and low current. At computational core block, usage of ultra low power microprocessor will be main factor in order to reduce the energy consumption of WSN system. The selection of microprocessor should be done carefully in such a way that its energy consumption is as low as possible without jeopardizing the overall WSN system.

The highest usage of energy in WSN is consumed by communication core block, which consists of transmitter, receiver and power amplifier. Typical solution to improve the energy consumption in WSN is by deploying high gain antenna to compensate low energy radio chipset in the communication core block. Another solution to reduce the energy consumption is the use of System on Chip (SoC) chipset whereby the computational process and computational cores are embedded in a single package [1,20]. Figure 3 shows the taxonomy of energy conservation in WSN [1]. The energy conservation could be achieved through optimization of duty cycling, data-driven or mobility-based schemes.

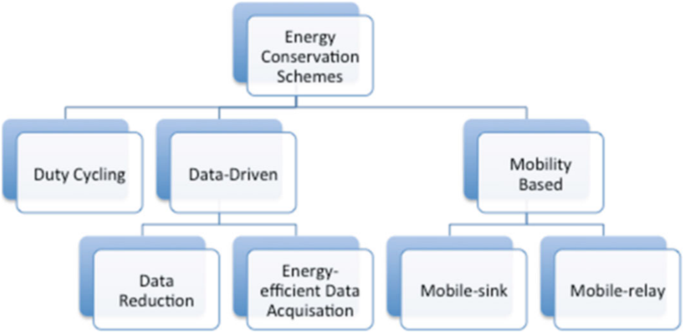

Fig. 3 Taxonomy of energy conservation in WSN

In data-driven method, the optimization can be done based on the data handling in the system either by reducing the data or by optimizing data acquisition through hierarchical or model-driven active sampling. In mobility based scheme the sensor node is configured to be achieved either by mobile-sink or mobile-relay. Sensor node could act as a full function device (FFD) or reduce function device (RFD). In FFD, the nodes never sleep, as it needs to relay the information from the RFD to the sink node. While an RFD will only wake at certain duration to gather the sensor data, forwarded to FFD and goes to sleep mode. As a sink node, the node requires high processing power to coordinate the whole network activity, thus, it requires the highest energy amongst the devices. The selection of sensor node functionality is purely depending on the network planning of the WSN system. In this paper, the optimization of the energy consumption in WSN will focus on the duty cycle scheme.

4 Duty Cycle Mechanisms in WSN

Duty cycle refers to the ratio of active periods over sleep periods of a sensor node [1] as depicted in Fig. 4. The duty cycle could be pre-configured or adapted depending on the network activity. In ideal case, the node will be set to enter sleep mode as long as possible to reduce the energy. However, the duty cycle must be manage in such a way that the latency is acceptable (too long sleep period) and the energy transition during wake time (too short wake up period). There are several duty circle mechanisms to improve the energy conservation in WSN applications such as DCLA [10], AMPE [16], DDCM [17], DDCM + LPB [17] and DBOP [18]. These duty cycle mechanisms will be reviewed and discussed in the following sub-sections.

4.1 Duty Cycle Learning Algorithm (DCLA)

The key to low duty cycle operation is as follows; Sleep—majority of the time, Wakeup—quickly start processing, and Active—minimize work return to sleep. The first mechanism

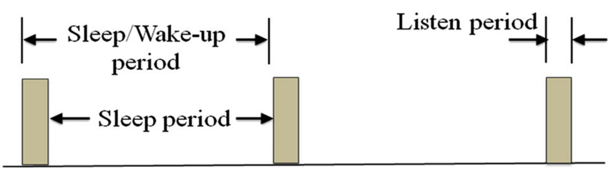

Fig. 4 Overview of duty circle mechanism in WSN

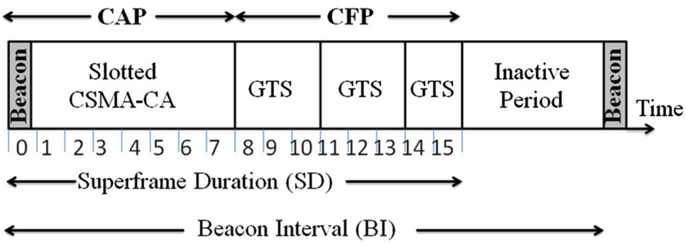

Fig. 5 The IEEE 802.15.4 superframe structure of beacon-enabled mode

under review is DCLA. This mechanism is deployed to consume the energy in application based on IEEE 802.15.4 standard. The balance between application's required delay and data delivery success is prioritized by DCLA. The DCLA is implemented in the IEEE 802.15.4 standard applications such as ZigBee by confirm a specific slots in the ZigBee superframe structure.

The beacon-enabled mode employs the superframe structure as shown in Fig. 5. The superframe duration is composed of contention access period (CAP) and contention free period (CFP). CAP is used by all devices based on a slotted carrier sense multiple access with collision avoidance (CSMA/CA) protocol to gain access and compete for the time slots. Meanwhile, CFP, a connection of three parts divided into guaranteed time slots (GTSs), is used for low latency applications. The first beacon with CAP, CFP, and inactive period is represented by two consecutive beacon frames, which in this case a beacon interval (BI). Then, the superframe duration (SD), which represents the nodes' active period in BI, is represented by the first beacon with CAP and CFP [10].

The modifications of IEEE 802.15.4 standard are not required for DCLA mechanism. The adaptive DCLA has to be set like a multi-armed bandit trouble wherever the agent's wants to be able to reduce both buffer overflows as well as idle listening. The modifications of the examination and utilization policies are normally based on the data feedback supplied through the system, and these actions are defined according the sleep schedules of the protocol. Furthermore, to find cooperation between beacon overhead and queuing delay, the MAC parameters of beacon order (BO) and superframe order (SO) are chosen. The coordinator estimates the delay and occupation in end devices' transmitting queues to adapt the duty cycle in DCLA. Hence, in order to avoid introducing more overhead, this information is embedded by using the three reserved bits of the frame control field as shown in (Fig. 6).

In [10], DCLA considers the FFDs as battery-powered devices. An FFD acts as the cluster head connecting a star of end devices that are collecting data in the region of it. In this case, the FFDs will not be able to forecast the data sent by other sensor nodes. They have

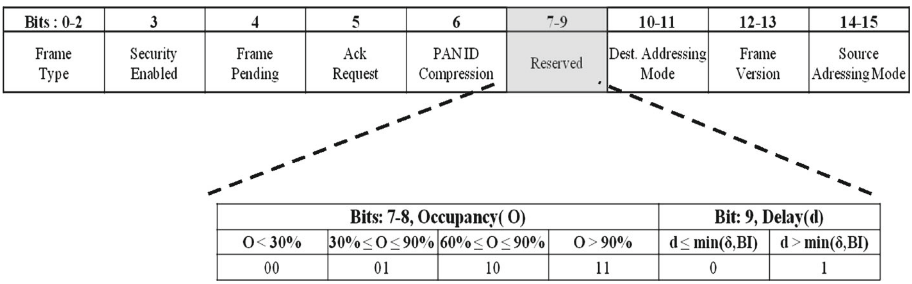

Fig. 6 The queuing occupancy and delay are embedded into the reserved bits of the MAC header control field

to be awake all the time in order to be able to receive all the collected data which will result of batteries depleting. To solve this difficulty, the beacon-enabled mode is defined by design of the standard. The transmission of beacon frame is supported by this mode from the coordinator to end devices to allow node synchronization. All devices are allowed by the synchronization to sleep between coordinated transmissions to reduce the idle listening in prolonged network lifetimes.

Low duty cycle in DCLA consumes less energy as compared to the high duty cycle. However, a small duty cycle causes buffer overflows and increases delays in the inherent resource constrictions of sensor nodes. In contrast, high duty cycle allows end devices to broadcast a higher number of data frames and reduces the delays. Moreover, high duty cycle might also enlarge the time which the coordinator expends in idle listening. As a result, the adaptation of duty cycle is crucial to improve the performance of IEEE 802.15.4 beacon-enabled systems. One of the methods for learning the duty cycle is by using the reinforcement learning (RL) framework [10].

4.2 Adaptive MAC Protocol for Efficient IEEE 802.15.4 (AMPE)

Another duty circle mechanism under review for energy conservation in WSN applications is AMPE. The main role of the AMPE protocol is to determine energy cost of communication and the efficiency for bandwidth sharing of wireless channel. In general, the suitable duty cycle will be chosen by the adaptive MAC protocol with respect to the load factor by means of adapting SO parameter. It is highly recommended for the network to have a one-tier topology with the coordinator situated in the middle. It is also recommended that in order to enable node to communicate directly with the coordinator the average range area of the transmission to be wide enough. There are two common modes for media access in IEEE 802.15.4 standard beacon-enabled and non-beacon-enabled.

If the beacon-enabled sensory device wants to transmit data, the protocol allows the transmission of packets whenever necessary. The nodes struggle to access the channel to transmit the required data at non beacon-enabled mode. When the transmission is completed, nodes move to an idle form till the next inquiry is received [26]. Figure 7 shows the superframe which consists of active period, inactive period and beacons [16]. However at the expenses of other devices transmission the modes are implemented in the AMPE based on the following superframe structure.

4.3 Distributed Duty Cycle Management (DDCM)

The DDCM mechanism was introduced by Alberola et al. In [17] specifically for beacon enabled WSN network. The function of duty cycle management is distributed between the

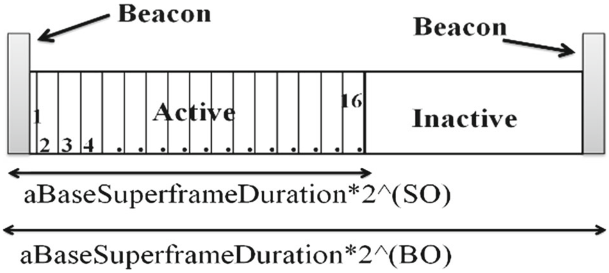

Fig. 7 The superframe structure of AMPE

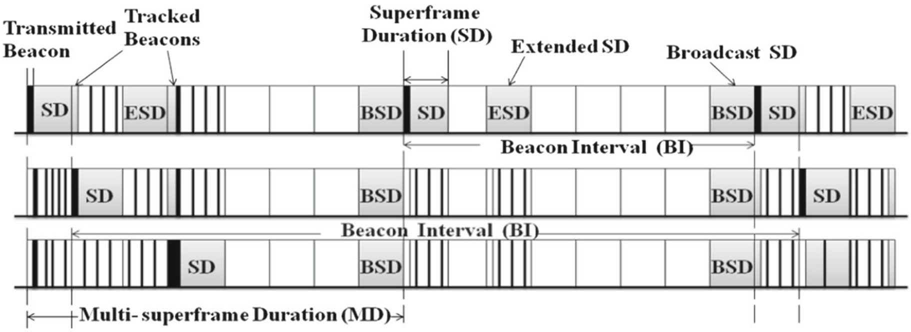

Fig. 8 The superframe structure of DDCM

sink/coordinator and sensor node. By having DDCM, beacon enabled coordinator could change the duty cycle by using two methods. The first method is by configuring the transmission of the BI and the second one is by reconfiguring the extra superframe duration (ESD) allocation.

Figure 8 shows the superframe structure of DDCM. In order to schedule a node *i* the scheduling algorithm is required. The multi-superframe duration (MD) is less than or equal to the sum of the superframe duration slots of its neighbours and neighbours' neighbour coordinators. DDCM identifies types of SD slot, a standard SD slot that includes a beacon frame and is repeated every BI as shown in Fig. 8. ESD is allocated for data transmission when the standard SD cannot handle with the incoming traffic. Moreover, broadcast superframe duration (BSD) is used for enabling broadcast communication among direct neighbours [17].

BI configuration relies on the traffic load (TL) of the network. The duty cycle increases once the TL exceeds certain threshold and decrease once TL is below certain threshold, to ensure the overall traffic load and duty cycle are maintained at optimum condition. The rate of the TL updates depends on the bandwidth utilization and queue occupancy of the data frame head. The allocation, de-allocation or reallocation of the ESD are based on first come first served basis and allocated within the multi superframe duration. Once ESD is being allocated, the radio receiver will be enabled for the entire duration of the superframe. Meanwhile, the neighboring devices will only enable the receiver if there is queue of data belong to them in the ESD slot. The duty cycle will be increased through allocation command and decreased through de-allocation command.

4.4 Distributed Duty Cycle Management + Low Power Broadcast (DDCM + LPB)

Distributed Duty Cycle Management + Low Power Broadcast mechanism is the extension of DDCM. This mechanism is equipped with a low power broadcast (LPB) feature. Based on the LPB feature, the nodes will only wake up during BSD when there are broadcast transmissions pending for them. Otherwise, it will still sleep even during BSD duration. By having this mechanism, the overall energy consumption could further be reduced significantly [17].

4.5 Distributed Beacon Only Period (DBOP)

The DBOP mechanism was introduced by Berta et al. In [18] based on earlier mechanism of the Beacon Only Period (BOP). As shown in Fig. 9, the DBOP mechanism has fixed BI periodicity and SD slots for receiving data; a node's duty cycle only varies based on

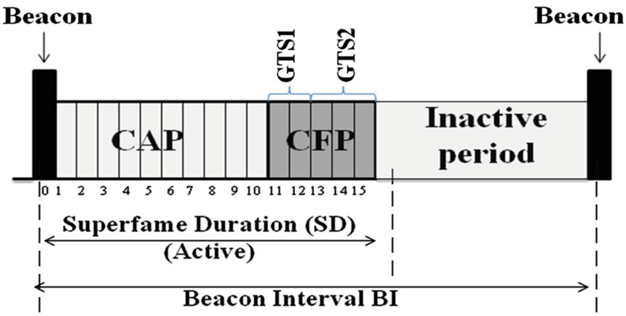

Fig. 9 The superframe structure of DBOP

the number of transmitted frames during neighbor's SD slots [18]. As in BOP, the beacon frame transmits between the neighbors and the neighbor's neighbors which are performed at different time slot. Each time slot contains the beacon and Turnaround Time (TT) which represent the duration between receiving and transmitting state [17,27].

In DBOP, the node needs to find the neighbor together with the empty slot. Additionally, the beacon order period length (BOPL) could dynamically change according to traffic condition. The BOPL is adopted through the associated device. If the BOPL is full, the node selects the next available slot and BOPL is increased by one. Direct neighbor will be notified through contention access period (CAP) by associated node. The beacon collision can be avoided through notification of BOPL by direct neighbor to neighbors' neighbor via beacon frame payload [17]. Meanwhile, DBOP does not perform efficiently due to the hidden collisions that happen in the used single SD slot. Furthermore, DBOP suffers from queue overflows as it does not carry out any duty cycle adaptation [18].

5 Performance Comparison of Duty Cycle Mechanisms Towards Energy Conservation

Based on the duty cycle mechanisms explained in the previous sections, the performance of the mechanisms toward the energy conservation in WSN applications are evaluated. The evaluations are carried out by comparing the different duty cycle mechanisms energy efficiency per node for different traffic loads. In DCLA mechanism a reversed bit has been defined in the time slot to measure the bit delay and timeslot occupancy. Based on this information, the duty cycle will be increased and decreased to conserve the overall energy of the system. In contrast, in comparison to AMPE mechanism [16], the duty cycle change with respect to the load factor depending on the SO parameters adaption. But in DDCM mechanism, the duty cycle changes according to the traffic load. The duty cycle adapts according to beacon transmission (BI) interval and ESD allocation. In DDCM + LPB mechanism, the duty cycle depends on the LPB. Finally, in comparison to DBOP mechanism [18] the duty cycle changes according to the length of the BOP.

DCLA mechanism has the best energy efficiency for RFDs because of duty cycle considers queue occupation and number of collisions at the device. Figure 10 shows the average energy efficiency vs. traffic load for RFDs for five different mechanisms. AMPE mechanism always uses the most suitable duty cycle and lets the coordinator to manage high and low bit rates. Therefore, the granted time slots are not taken into account, while this case is considering only the transmissions within the CAP. As a result, the performance of AMPE mechanism is slightly lower compared to DCLA mechanism as shown in Fig. 10. Figure 11 indicates that

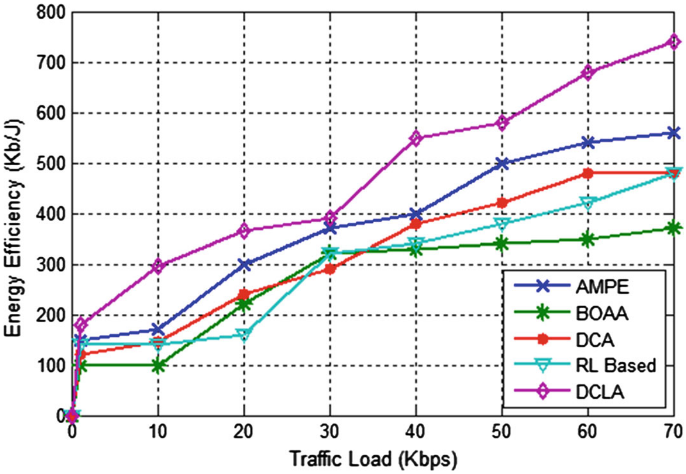

Fig. 10 Average energy efficiency versus traffic load for five different mechanisms for RFDs

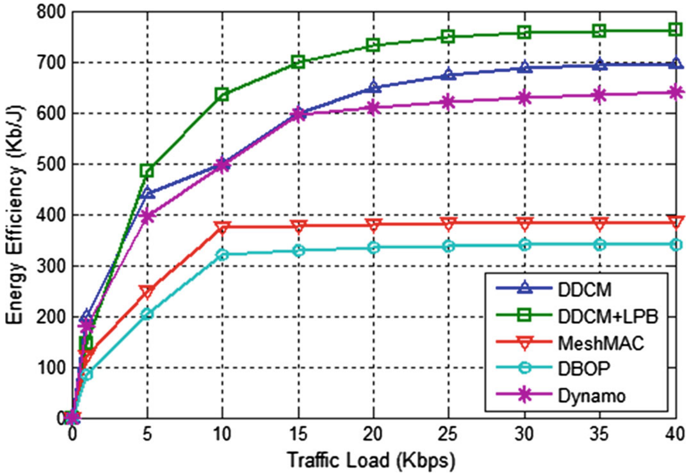

Fig. 11 Average energy efficiency per node

the DDCM + LPB mechanism provides high energy efficiency per node as compared to the other mechanisms when the traffic loads are increase. Moreover, the performance of DBOP mechanism indicates the lowest energy efficiency with respect to traffic load performance in comparison to other mechanisms.

Figure 12 shows the comparison of the average energy efficiency versus traffic load per node for each mechanism. Moreover, from energy conservation point of view, DDCM + LPB mechanism provide the most efficient energy comparison compared to other mechanisms. This is mainly due to adaption of duty cycle based on traffic load. On the other hand, the worst and unstable performer is AMPE mechanism due to the adaptive MAC protocol which is able to select the proper duty cycle with respect to the load factor by means of adapting SO parameter. Finally, the summary of various discussed duty cycle schemes for WSN is shown

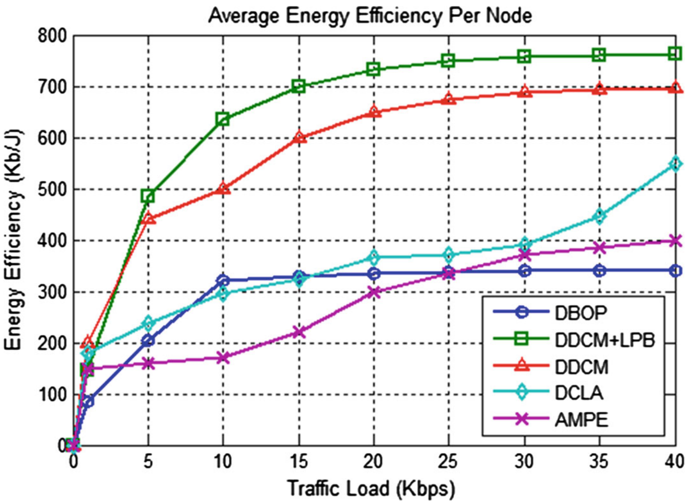

Fig. 12 Comparison of average energy efficiency per node

in Table 1. Table 1 shows a comparison between the five mechanisms. Also Fig. 12 shows a comparison between the five proposals; this figure shows that DDCM + LPB mechanism has the highest energy efficiency per traffic load, but it is the only one that consider as a mixed mechanism (with LPB) in order to conserve the energy.

6 Conclusion

This paper reviews and compares the performances of different energy conservation mechanisms by using duty cycle management schemes at MAC layer for IEEE 802.15.4 standard. These mechanisms are DCLA, AMPE, DDCM, DDCM + LPB and DBOP. Each of these mechanisms is managed to improve the energy efficiency depending on the traffic load. These duty cycles based mechanisms change their parameters such as idle listening, packet accumulation and delay at the end device transmitting queue to improve the WSN applications energy consumption. In AMPE mechanism, the MAC protocol is able to select the proper duty cycle with respect to the load factor by means of adapting SO parameter. In DDCM mechanism, the purpose of duty cycle management is distributed between BI and ESD which adapt to traffic load condition much faster by changing the duty cycle. The next generation of DDCM which is DDCM + LPB further improves DDCM by optimising the node's energy consumption through low power beacon. The DBOP mechanism changes the duty cycle through BOPL. As a result, the energy efficiency of DDCM + LPB mechanism outperforms DDCM by average of 10 %. Also, it makes approximately 100 % enhancement in terms of average energy efficiency compared to AMPE mechanism. Hence, the DDCM + LPB mechanism provides the best energy efficiency in WSN applications compared to other mechanisms. It is because the DDCM + LPB mechanism adapts the duty cycle according to the network traffic load. Once the traffic load increase, the duty cycle will also increase accordingly and vice versa.

Table 1 The comparisons of discussed duty cycle schemes for WSN

Criteria	Barbieri [16]	Villaverde [18]	Alberola [17]	Alberola [17]	Alberola [10]
Duty cycle schemes	AMPE	DBOP	DDCM	DDCM + LPB	DCLA
Layer	MAC	MAC	MAC	MAC	MAC
Duty cycle energy optimization	–	Duty cycle change through beacon order period length (BOPL)	Duty cycle change through BI ESD	Low power beacon (LPB)	Duty cycle change based on idle listening, packet accumulation and delay in end device transmitting queue
Goals	To reduce duty cycle energy consumption	To reduce duty cycle energy consumption	To reduce duty cycle energy consumption	To reduce duty cycle energy consumption	To reduce duty cycle energy consumption
Energy efficiency [(NOL = 30 kbps (kb/J)]	370	339	688	757	390
Year of publication	2006	2010	2011	2011	2012

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