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Survey of Dynamic Super-Frame Adjustment Schemes in Beacon-Enabled IEEE 802.15.4 Networks: An Application's Perspective

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Abstract IEEE 802.15.4 targets low data rate communication with limited power devices and cheap wireless networking solutions. In recent years both industry and academia are attracted to IEEE 802.15.4 because of its applicability in wireless sensor networks and wireless body area networks. An important feature of IEEE 802.15.4 is its very low duty cycle operation for conserving energy consumption of sensor device. Super-frame structure of IEEE 802.15.4 defines the duty cycle of nodes. The super-frame structure is based on two parameters: beacon order (BO) and super-frame order (SO). The performance of an IEEE 802.15.4 network depends on the values of BO and SO. These values depict the energy consumption, throughput, node discovery and latency of communication. IEEE 802.15.4 uses fixed BO and SO values which can be carefully chosen to meet the network requirements. In this paper, an extensive survey of dynamic super-frame adjustment algorithms is presented. The survey focuses on beacon-enabled star topology of IEEE 802.15.4 and studies the impact of aforementioned algorithms for various applications. Also, the survey categorizes common IEEE 802.15.4 applications based on their requirements for super-frame adjustment. A brief simulation analysis is included in this survey to highlight the impact of BO and SO on the network performance.

Keywords IEEE 802.15.4 · Super-frame adjustment · Dynamic duty cycling · Beacon-enabled mode

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1 Introduction

The IEEE 802.15.4 [1] is designed for low rate wireless personal area networks. It provides low data rate communication over limited power wireless devices and cheap wireless networking solutions. LR-WPANs are envisioned for monitoring, situational awareness, asset location tracking, industrial automation and control. IEEE 802.15.4 standard defines the physical and MAC layers for WPANs in order to deal with the node limitations (energy, memory and processing) [2]. IEEE 802.15.4 standard specifies rules for the establishment of different network topologies: star and peer-to-peer, network operation modes: beacon enabled and non-beacon enabled, and channel access mechanisms: contention based and non-contention based.

IEEE 802.15.4 network comprises of fully functional devices (FFDs) and reduced functional devices (RFDs). FFDs have more computational capability and energy resource as compared to RFDs. Moreover, FFDs support all network functionalities whereas RFDs contain limited network implementation. This work is focused on star topology based beacon enabled networks. Star topology is suited for short range (few meters) small networks. It comprises of one FFD generally referred as Personal Area Network (PAN) coordinator and connecting devices (FFDs and RFDs). Growing number of applications in body area sensor networks, industrial automation, and smart environments use star topology based networks. Star topology is especially useful in networks where low power operation is required. Low operation is supported in IEEE 802.15.4 using periodic sleep and wake intervals.

In a beacon enabled network, the PAN coordinator periodically issues beacons. The beacon frame includes information related to PAN identification, synchronization, and super-frame structure. Super-frame structure describes various parameters related to a PAN but most importantly it defines the duty cycle of nodes. Duty cycle can be increased and decreased according to applications energy requirement, data rate and delay. However, the current IEEE 802.15.4 standard does not allow dynamic adjustment of super-frame structure depending upon network conditions. The standard recommends using fixed super-frame structure, which is manually tuned by the network administrator during network deployment phase. A number of research efforts [3–15] have been made in recent years to dynamically adjust the duty cycle of nodes in beacon enabled star topology based network with multi-fold objectives of extending network life time, increasing throughput, decreasing latency and lowering contention.

This paper surveys the recent research efforts on dynamic duty cycle adjustments of IEEE 802.15.4 standard in star topology based network. Also, the survey evaluates the existing duty cycle adjustment schemes to determine their applicability and suitability for different WPAN applications. The research contributions of this article are as follows.

- Highlighting common applications of IEEE 802.15.4 with requirement for dynamic super-frame adjustment.
- Impact of super frame parameters on network performance: throughput, network life time and latency.
- In depth survey of existing duty cycling schemes

The remaining part of this survey paper is organized as follows; Applications of IEEE 802.15.4 is discussed in Sects. 2, 3 outlines the IEEE 802.15.4 beacon enabled mode.

IEEE 802.15.4 duty cycle adjustment schemes and their impact is discussed in Sect. 4. Discussion is presented in Sect. 5. Last section concludes this research work.

2 Applications of IEEE 802.15.4

This section briefly describes the applications of IEEE 802.15.4 along with their requirements and design challenges. A number of wireless PAN applications are proposed that can be categorized into different domains: health, surveillance, industrial and agriculture, commercial and entertainment. Table 1 presents the aforementioned applications along with their network requirements. In the remaining of this section, we briefly discuss the above mentioned application domains of IEEE 802.15.4.

Table 1 Application requirements of IEEE 802.15.4 based networks

Area	Applications	Data (kbps)	Latency	Throughput	Network life time	Duty cycle
Health/medical monitoring using BASNs	Implantable cardiac defibrillator (ICD) [16] ECG [17, 18] monitoring patient's location and health conditions [29]	Scalar, video, images	Low	High	Months to years	Dynamic
Surveillance/ military	Image based sensor network [30] location alertness, individual detector/ locator, battlefield observation, military condition awareness, detection of enemy units [34–37]	Scalar, images, video	Low	Medium	Months	Dynamic
Industrial and agriculture	Industrial automation [38] factory process controlling manufacturing process monitoring [39–43] salinity, pH, temperature and soil-moisture, greenhouse [44–47]	Scalar, images, video	Low	High	Years	Fixed/dynamic
Commercial and entertainment	Smart homes, buildings [49–54, 60], smart meter [61], Entertainment [55]	Images, Video	Low	High	Months	Fixed/dynamic

Throughput: Low (bps), Medium (Few kbps) and High (Hundreds of kbps)

Latency: Low (delay bound), Medium (real time), High (best effort)

Data: Scalar/Acoustic/Video/Image

Network life time: Years/Months/Days

2.1 Healthcare Applications

Monitoring different activities of interest is a part of our daily life and an integral part of healthcare. IEEE 802.15.4 based low power networks are an excellent choice for body area networks that comprises of sensor devices in and on the body. In-body applications include monitoring vital organs status using pacemakers, implanted drugs, swallowed camera pills and implantable cardiac defibrillator (ICD) [16]. On-body applications are monitoring ECG [17–19], pulse rate, blood pressure and temperature [20–23]. Some non-medical applications that are related to healthcare are monitoring fall detection, forgotten things, assessing soldier fatigue and battle readiness.

Different data reporting models are used in BASNs [24, 25]: on-demand, periodic and emergency. On-demand reporting is used by the doctors for the purpose of diagnostic; this traffic is normally requested by the observer (doctor) of the patient. Periodic reporting is used to regularly update the backend system about the latest status of the monitored patient. Emergency reporting is carried out when some sensor sense a critical event that must be notified immediately. The nature of data in BASNs is generally scalar in nature. However, acoustic and multimedia data is also transmitted by some applications [26, 27]. Different priorities are given to video data coming from sensors on ambulances, audio traffic from aged people, and images returned by sensors placed on the body [28]. Overall data rate in a typical BAN can vary from few kbs to tens of kbps [29]. IEEE 802.15.4 uses fixed duty cycle approach as a result nodes follow same wakeup and sleep schedules. Although, this approach enhances network lifetime under low network traffic but under variable traffic rates it can results in high latency, low throughput and decrease in network life time. As a result, the fixed duty cycle operation of IEEE 802.15.4 standard is not suited for healthcare applications.

2.2 Surveillance Applications

Surveillance is the monitoring of object or area of interest for the purpose of security. Image based sensor network [30] and wireless multimedia sensor networks (WMSNs) [31–33] can employ IEEE 802.15.4 for underlying infrastructure. IEEE 802.15.4 based clustered tree or mesh topology is used to create larger networks with more coverage area. Typical applications related to surveillance include intrusion detection, location alertness, individual locator, battlefield monitoring, military condition awareness and detection of enemy units [34–37].

The data rate of surveillance applications using multimedia content can vary extremely under normal and emergency conditions. Under normal conditions periodic scalar data is generally sent to the base station whereas, in case of an event video content can significantly raise the data rate. In variable conditions, the fixed duty cycle approach of IEEE 802.15.4 can result in high end-to-end latency that can lead to packets arriving at the destination after their play-out times. Hence, dynamic super-frame adjustment is imperative for the correct adaptation of duty cycle, that can result in enhanced packet delivery and decrease in end-to-end delay.

2.3 Industrial and Agricultural Applications

IEEE 802.15.4 based WPANs are growingly used in the industry for industrial automation, factory process controlling, monitoring and control of industrial equipment and manufacturing process monitoring [38–43]. The primary focus of industrial usage of WPANs is to provide high quality products, increased safety standards for workers and decreased production time. WPANs are used in agriculture for the monitoring of green-house [44, 45] salinity, pH, temperature and soil-moisture in the form of images and video surveillance [46, 47]. Sensors are buried in soil for the purpose to enhance crops quality and production.

The aforementioned applications deploy different types of sensors to observe their relevant environment but the nature of reported data is mostly scalar in nature. Data can be transmitted periodically or on event occurrence. The prime concern in above mentioned applications is enhanced network life for long term monitoring purpose. Due to low data rate and long term WPAN operation requirements, fixed low duty cycle operation is suitable for most of industrial and agricultural applications. On the other hand, latency of event reporting can increase in this case therefore, for time bound event delivery can be affected by lowering duty cycle.

2.4 Commercial and Entertainment Applications

The most popular commercial applications are smart environments including homes, buildings and cities [48–53]. Different aspects in buildings such as, heating, air conditioning, light control, metering and security systems can be effectively controlled using WPANs. Other commercial usage of IEEE 802.15.4 sensors are for pressure monitoring, baggage tags, inventory management and smart billing system. Commercial and entertainment [54, 55] applications are focused on offering comfort, relaxation and convenience to its users.

Requirements of aforementioned applications can range from extremely low data rate temperature sensing in smart buildings to high data rate audio/video transfers in

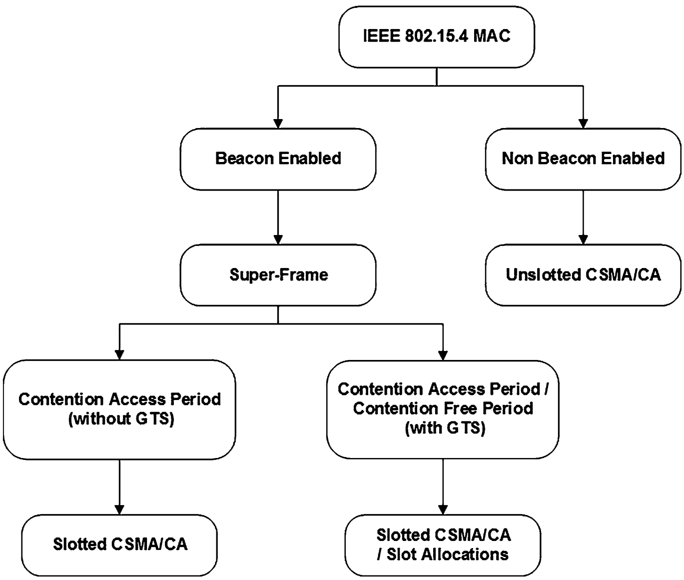

Fig. 1 IEEE 802.15.4 operational modes

entertainment applications. As a result, dynamic duty cycle operation can be useful in most application scenarios for enhanced network performance.

3 IEEE 802.15.4 Beacon Enabled Mode

In this section, we briefly discuss the MAC layer of IEEE 802.15.4 standard in beacon enabled mode. Figure 1 illustrates the IEEE 802.15.4's mode of operations. Non beacon enabled mode is an example of infrastructure less mesh network whereas beacon enabled mode is infrastructure based star or cluster-tree topology based network.

Beacon-enabled mode uses super-frame structure as shown in Fig. 2. The duty cycle of node is the ratio of active period to the inactive period. Inactive period is the time during which the coordinator and nodes stay in sleep mode (low power mode). The active period is further divided in contention access and contention free periods. The duty cycle is depicted by two parameters: BO and SO. The length of beacon interval (BI) is defined by BO, after every BI the coordinator issues a new beacon. SO defines the length of active period or super-frame duration (SD) within a single BI. In star topology, the PAN coordinator communicates the key super frame parameters BO and SO for the current BI within the beacon frame. BI and SD duration is not only responsible for duty cycle determination but also impacts the throughput, interference and end-to-end data delivery delay within the network. The active period of super frame consists of 16 time slots of same length. Each slot denotes minimum number of symbols (60 symbols per slot) if SO is set to 0. The following equations illustrate how BI and SD is determined based on BO and SO.

$$aBaseSuperFrameDuration = aBaseSlotDuration * aNumSuperframeSlot \quad (1)$$

$$BI = aBaseSuperFrameDuration * 2^{BO} (0 \le B0 \le 14) \quad (2)$$

$$SD = aBaseSuperFrameDuration * 2^{SO} (0 \le SO \le BO \le 14) \quad (3)$$

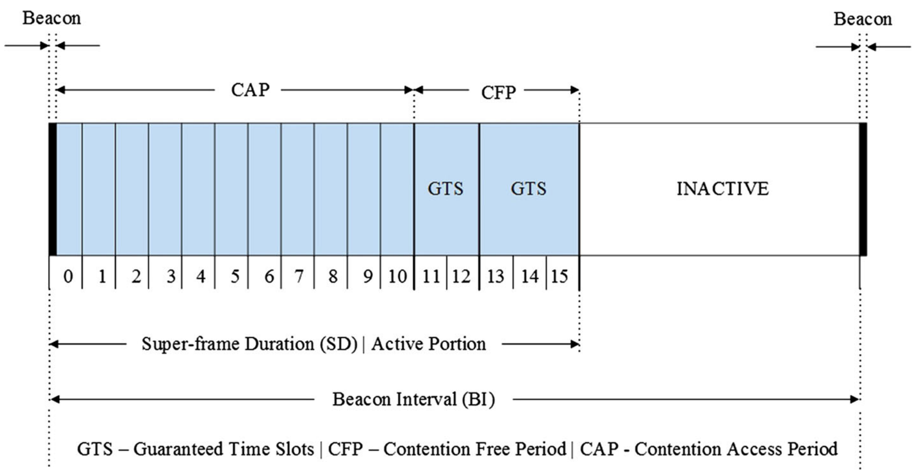

Fig. 2 IEEE 802.15.4 super-frame structure

$$Dutycycle\,(DC)\ = \frac{SD}{BI} \tag{4}$$

As an example, we calculate BI, SD and duty cycle at BO = 5 and SO = 4. aBaseSlotDuration = 60 symbols aNumSuperFrameSlots = 16 slots

$$aBaseSuperFrameDuration\ = 60 * 16 symbols\ =\ 960 symbols \tag{5}$$

$$BeaconInterval = BI\ =\ 960 * 2^5\ symbols\ =\ 491.52\,ms \tag{6}$$

$$Super - frameDuration\ =\ SD = 960 * 2^4\ symbols = 245.76\,ms \tag{7}$$

$$Duty\,cycle = DC = 0.5 \tag{8}$$

In the above scenario, the PAN coordinator will generate about two beacons each second. During each beacon interval, the devices will be in active mode for 245.76 ms out of 491.52 ms of BI. Therefore, the duty cycle is 50 %. This result means about 50 % of energy reduction can be possibly saved. The detailed settings of BO and SO is shown in Table 2, in which the duty cycle is kept fixed at 50 %.

3.1 Impact of Super-Frame Parameters on Network Performance

In this section, the impact of two important IEEE 802.15.4 super frame parameters BO and SO is analysed against network life time, throughput and latency. IEEE 802.15.4 standard suggests using fixed BO and SO values. This requires fine tuning of these parameters against network size, density and application requirements of data rate and network life-time. This is efficient for applications with low data rate and periodic sensing [56]. It is not suitable when the traffic load is variable and delay bound delivery of data is required. Considering, small values of SO as compared to BO results in low throughput and high delays due to small active portion within the BI. Energy consumption and contention increases as BI is lowered.

Table 2 Change in BI, SD, sleep period and beacons per second with respect to different BO and SO values

BO	SO	BI (ms)	SD (ms)	Sleep period (ms)	Beacons (per sec)
1	0	30.72	15.36	15.36	32 per sec
2	1	61.44	30.72	30.72	16 per sec
3	2	122.88	61.44	61.44	8 per sec
4	3	245.76	122.8	122.8	4 per sec
5	4	491.52	245.76	245.76	2 per sec
6	5	983.04	491.52	491.52	1 per sec
7	6	1966.08	983.04	983.04	After every 2 sec
8	7	3932.16	1966.08	1966.08	After every 4 sec
9	8	7864.32	3932.16	3932.16	After every 8 sec
10	9	15,728	7864.32	7864.32	After every 16 sec

In order to validate the above mentioned claims, we conduct simulations in NS-2 [57]. The simulation scenario consists of a star topology beacon enabled network with 15 nodes randomly positioned in 15 m range. The energy model of nodes are mirrored according to ATMEL mote [58]. Each simulation is run for 10 times and average results are shown. Simulation settings are listed in Table 3.

Throughput of IEEE 802.15.4 at different data rates using SO equal to BO and half of BO is shown in Fig. 3. At all data rates the observed throughput using SO half of BO is less than SO equal to BO. Also, it can be observed at higher data rates of 100 and 150 kbps that reducing active portion to half, severely degrades the observed throughput because of increased contention between transmitting nodes. At BO = 12, the BI is 62.9 s whereas, the SD is 0.98 s only. As a result, the throughput is very low because active duration is too small as compared to inactive duration. Also, it is worth mentioning that further decreasing SO beyond less than half of BO will further reduce the throughput. Another important fact is when BO exceeds 10 the throughput slightly effected due to the loss of connectivity between PAN members and coordinator because of high beacon interval.

The average end-to-end delay at different BO and data rates as observed at the PAN coordinator is shown in Fig. 4. When SO is equal to BO there is no inactive portion within the super-frame and nodes can transmit data immediately once they obtain the medium. The delay increases as the active portion (SD) decreases compared to the inactive portion when SO is half of BO. In this case, the nodes do not get the opportunity to transmit packets as they are mostly in the inactive portions, therefore the packets remain in the buffer resulting in higher delay.

The average percentage of energy consumed by a single source node at different BOs and data rates is shown in Fig. 5. When SO is equal to BO, the energy consumption is high because there is no inactive portion and the nodes can uninterruptedly communicate with the PAN coordinator. When SO is half of BO, then the percentage of energy consumption decreases because the active portion is very less and nodes spend most of their time in active mode

Table 3 Simulation parameters

Parameter	Value
Simulation time	500 s
Radio range	15 m
Frequency band	2.4 GHz
Beacon order	2, 4, 6, 8, 12
Super-frame order	Half of BO and equal to BO
Traffic type	CBR
Packet size	50 B
Source nodes	5
Data rate (kbps)	10, 100, 150
Initial energy	4 Joules
Transmit mode	12.3 mA
Receive mode	14 mA
Sleep mode	0.02 A
Idle mode	0.4 mA

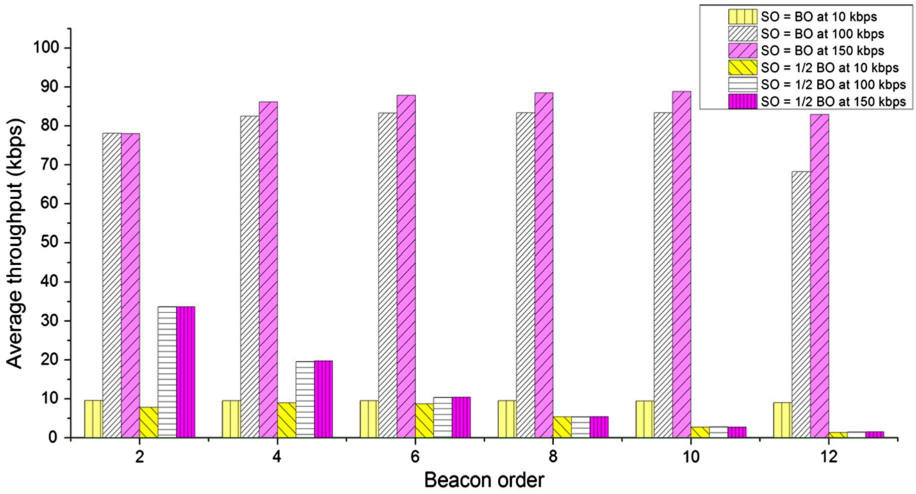

Fig. 3 Throughput of IEEE 802.15.4 at different data rates and using SO equal to BO and SO half of BO

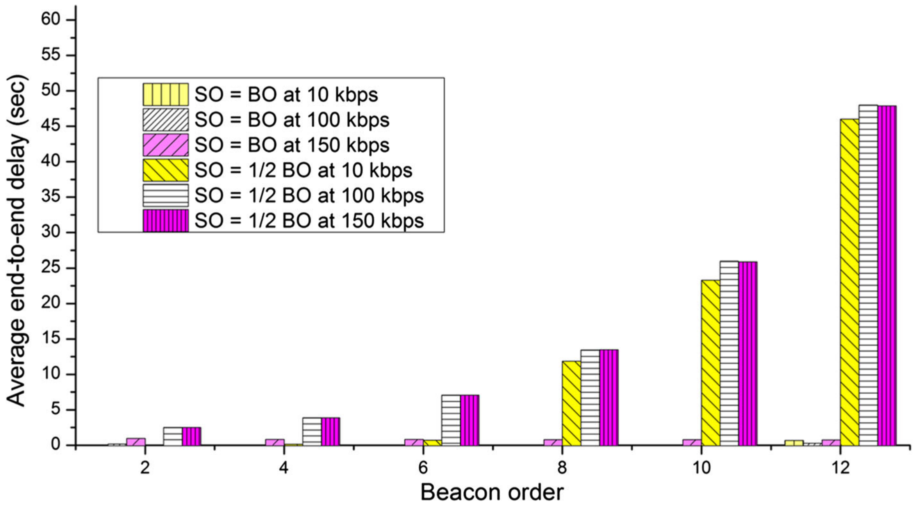

Fig. 4 Average end-to-end delay at SO equal to BO and SO half of BO

4 Superframe Adjustment Schemes

This section presents the existing super frame adjustment schemes and their impact on network performance. In existing literature, the efforts are mainly focused at enhancing the performance of beacon-enabled networks by changing either BO [3, 4] or SO [5–14]. But some recent research efforts have shown increased network performance by simultaneously changing both BO and SO [15]. In the remaining of this section the aforementioned super-frame adjustment schemes are discussed.

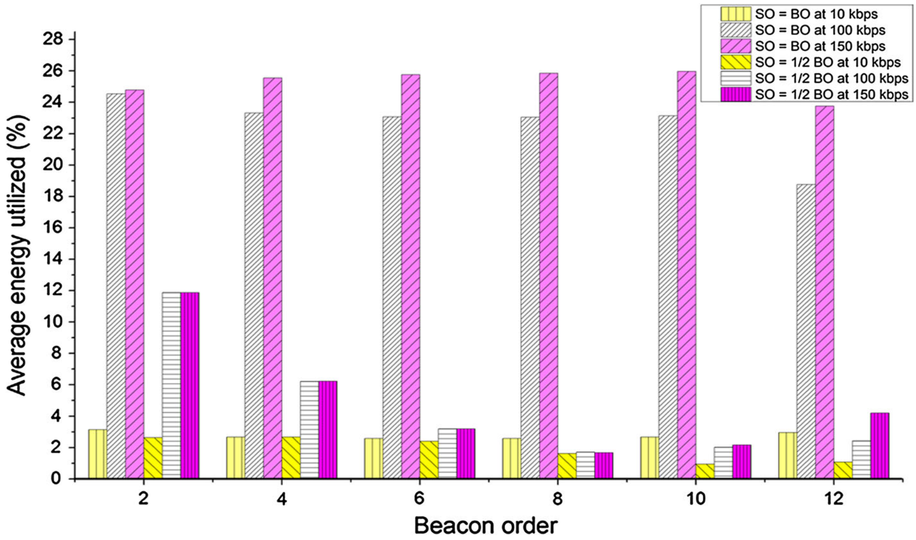

Fig. 5 Average energy utilized at SO equal to BO and SO half of BO

4.1 Dynamic BO Adjustment

Network lifetime can be enhanced by lowering the duty cycle of nodes with dynamic adaptation of BO and setting SO to a fixed value appropriate to data collection rate [3, 4]. The beacon order adaptation algorithm (BOAA) [3] and individual beacon order adaption algorithm (IBOAA) [4] uses BO adjustment for power saving purposes. These schemes tend to elongate the sleep mode of nodes by increasing BI during idle network state. These schemes work efficiently for networks with low data rates and periodic scalar data reporting.

In [3], the work is carried out for star topology comprising of static nodes. Dynamic BO directly impacts the duration of the duty cycle in WPAN, as SO is kept fixed. If BO value is high compared to SO then the in active portion will be more than active portion within a BI. However, during data reporting the throughput will be less and latency would be relatively high. In [3], the coordinator adjusts the BO according to the amount of observed traffic during a BI. If data traffic increases then BO is lowered whereas during idle beacon intervals BO is increased.

Another dynamic BO adjustment scheme IBOAA [4] is focused on lowering the power consumption and at the same time striving to ensure the end-to-end delay requirements of traffic. In case of high BO and small SO the inactive portion of super frame can be much greater than active portions. Packets will wait in the nodes queue and end-to-end delay will increase. Therefore, each node in IBOAA scheme sets a traffic queue flag to one if it has pending data to send whereas, its set to zero if no data is available in a nodes queue. The PAN coordinator based on the status of incoming queue flags from the transmitting nodes adjusts the BO for the next interval.

Dynamic BO adjustment schemes [3, 4] select a fixed value of SO whereas BO values are changed to enhance the network performance. But what is the ideal value of SO to be used in a network is not investigated by these schemes. The value of SO is more important than BO because it defines the active portion and hence the duty cycle of nodes.

4.2 Dynamic SO Adjustment

Most of the research efforts [5–14] related to dynamic super frame adjustment for lowering the duty cycle of nodes and enhancing network life time are focused on adapting SO and keeping BO fixed. The duty cycle algorithm (DCA) [5] adjusts SO at the coordinator by considering different parameters of end devices including queue size, queuing delay, energy consumption per bit and data rate. This information is provided by the PAN nodes to the coordinator. However, DCA does not consider traffic deadlines for adjusting duty cycle. Also, DCA uses a fixed BI that can increase energy consumption if small BO is used. Even under no or light network load nodes will be forced to periodically wakeup and listen to the beacon. Using fixed high values of BI can increase association time of nodes and can result in higher initial latency of event reporting.

An Adaptive algorithm to optimize the dynamics (AAOD) [6] dynamically adjusts the SD duration to accommodate the network traffic with the objective of increasing packet delivery ratio. The coordinator calculates the number of received packets in each super-frame and compares them with the received packets in the previous super-frame duration. If the amount of received packets increases from a fixed threshold, coordinator starts increasing the SO. AAOD [6] uses a very simple algorithm that does not take into account other network parameters like congestion level and traffic deadlines.

The dynamic super-frame adjustment algorithm (DSAA) [7] alters only the SD duration by changing the SO whereas BO is fixed. The main goal of DSAA is to decrease the power consumption and to improve channel utilization. At the end of each SD, the coordinator calculates the super-frame occupation and collision rate. The occupation rate is the percentage of time the coordinator was busy receiving or transmitting data to the duration of time it was idle during the SD duration. Collision rate is calculated based on the received data at the coordinator to the expected data during the SD duration. The coordinator compares these values to certain predefined application specific thresholds and adjusts the length of the active period for next super-frame.

An Adaptive MAC protocol (AMPE) [8], adjusts the duty cycle based on the occupied proportion of the super-frame. In this algorithm, first coordinator calculates super-frame occupation ratio, and compares it with two different application specific thresholds: upper and lower thresholds. If the super-frame occupation ratio is greater than the upper threshold, the coordinator increases SO and if that is less than the lower threshold, then coordinator decreases SO.

In Adaptive Duty Cycle Algorithm (ADCA) [9] algorithm coordinator selects the SO for each super-frame according to idle time, throughput during CAP and queue state of nodes. If the length of idle time is more than half of the CAP portion coordinator decrease SO for the next super-frame. If the idle time is less than half of the CAP portion, then coordinator compares the number of received packets and the number of pending packets during the CAP. If pending packets are greater than received packets then SO is increased for the next BI. Also, ADCA [9] considers packet drops during the CAP duration for adjusting the SO.

Some algorithms [10, 11] adjust the traffic in the contention aware period (CAP) of the super frame without adjusting BO or SO. In [10], the concept of I-tone is introduced that is a busy tone transmitted by nodes to the PAN coordinator after CAP. This tone indicates that the node was unable transmit at all data due to the heavy traffic. Every time a node receives a beacon from PAN coordinator, it resets I-tone to IDLE that means the node has not attempted to transmit a packet. In order to transmit a packet, the MAC layer performs clear channel assessment (CCA) if it fails the node changes its data transmission status to failure and I-tone is transmitted. On the other hand, success of CCA and ACK from coordinator indicates a successful transaction. The I-tone in [10] is used by the coordinator to determine the status of information delivery during the CAP duration. However, this scheme [10] does not propose any mechanism for dynamic duty cycle adjustment. In [11] an algorithm is proposed to adjust the active period of CAP for adjusting real time packets. Nodes that fail to send their real time packets during active period can indicate this to coordinator using a request packet. In this case, the coordinator immediately extends the duration of active period to adjust real time traffic. Another work [12] presented a new model in which the nodes that could not send their packet in active period can send packets in time intervals of inactive period called sentinel duration.

In [13], Markov-base theoretical analysis is proposed for energy saving and to meet the application requirements. Also, a solution based on augmentation learning is presented in [14]. Both [13, 14] are based on mathematical models and show good precision in how SO and BO parameters should be adjusted based on network conditions. However, these models are designed by considering fixed network traffic patterns and require fine tuning of different variables. These models [13, 14] are not validated using simulations or test beds.

As summary of dynamic SO and fixed BO schemes, they can increase throughput, decrease latency, and enhance network life. Over increase in SO than required under current network conditions will increase energy consumption. On the other hand, low value of SO can result in less throughput, higher contention and more delays in data delivery. An important question regarding dynamic SO and fixed BO schemes [5–14] is finding the ideal BO that should be used in the aforementioned schemes. Setting fixed BO at higher values can result in synchronization and connectivity issues for PAN members whereas lower BO values can increase network power consumption.

4.3 Dynamic BO and SO Adjustment

The network performance can also be optimized by changing both SO and BO values simultaneously [15]. Duty cycle self-adaptation algorithm (DBSAA) [15] adjusts the duty cycle based on adjusting both BO and SO parameters in IEEE 802.15.4 based networks. Network coordinator adjusts the BO and SO dynamically by considering four estimation parameters; super-frame occupation ratio (OR), the collision ratio (CR), the number of packets received by the coordinator and the number of source nodes. In the DBSAA algorithm [15], the CAP portion is adjusted in a star topology under beacon enabled mode operation. DBSAA is based on the findings presented in [11]. DBSAA follows three steps; firstly, it estimates network load, secondly it determines changes in the network load, thirdly it assigns the number of BI that the coordinator should wait before applying the DBSAA algorithm. However, DBSAA assumes same data rate of all network nodes and does not consider time bound data during event reporting. DBSAA [15] shows increased network performance by simultaneously changing of both BO and SO values.

5 Discussions

The impact of BO and SO on network performance is vital. Both these parameters collectively depict the throughput, latency, reliability and network life time. The performance of existing super frame adjustment schemes with respect to aforementioned metrics is shown in Table 4. The type of super frame adjustment strategy used (fixed or variable) by different existing protocols and their impact on the throughput of the network, latency of communication, reliability of data exchange and overall network time are presented in Table 4. The grading strategy of low, medium and high is used with respect to the highest achieved results that are presented in existing literature related to super frame adjustment protocols. Existing schemes have used different metrics for adjusting BO and SO including occupancy ratio [8, 15], collision ratio [8, 9, 15], fixed traffic type [59], topological changes [6, 15], latency [6], super-frame efficiency [8], Back off exponent [6, 9], number of devices in the network [5, 15], traffic load [6], idle time, queue state [9], channel status [15] and network life time [5, 12].

Adjusting BO dynamically while keeping SO fixed can give better results as compared to standard IEEE 802.15.4 implementation. But defining a fixed value of SO with respect to BO is difficult and again requires fine tuning just like IEEE 802.15.4. Considering fixed SO at 4 means that BO can never be less than 4 as SO is fixed. As a result, during idle network operations nodes cannot save energy aggressively by further decreasing SO. Although, this is partially achieved by increasing BO but higher values of BO may cause synchronization problems resulting in loss of association between member nodes and PAN coordinator. Moreover, small fixed value of SO e.g., 2 or 3 can initially cause more latency in communication that is decreased by lowering BO. Small BO means lowering BI that will cause frequent beacon transmissions and increased network congestion.

Alternate approach is dynamic SO and fixed BO that is considered by major duty cycle schemes [5–15]. In this approach, selecting a fixed value of BO is an important network performance indicator. Since BO is responsible for number of beacons over the network therefore it should be moderately selected between four to eight. A further increase in BO may result in synchronization issues between PAN members and the PAN coordinator. Dynamic SO adjustment schemes can provide better network throughput if BO is considerably large so that frequent beacons should not interfere with network operations during high network load. In this scenario, SO can be increased to provide nodes with the opportunity to contend more during the active duration of CAP.

Recently [15] both BO and SO are dynamically adjusted to provide even better network performance. Apart from other network performance metrics this solution can especially provide balance between achieving throughput and extending network life time. By not restricting either BO or SO to a fixed value these can be adjusted to their limits as defined by IEEE 802.15.4 standard. Hence, during idle network operations values of SO and BO

Table 4 IEEE 802.15.4 super frame adjustment protocols

Protocols	Type of BO and SO	Throughput	Latency	Reliability	Network life time
IEEE 802.15.4 standard	BO = Fixed SO = Fixed	Low	High	Medium	Medium
BOAA [3], IBOAA [4]	BO = Variable SO = Fixed	Medium	Medium	Medium	Medium
DCA [5], AAOD [6], DSAA [7], AMPE [8], ADCA [9]	BO = Fixed SO = Variable	High	Low	Medium	Medium
DBSAA [15]	BO = Variable SO = Variable	High	Low	High	High

can have large difference for conserving energy whereas this can be decreased to lower latency of communication. Still the issue of dynamic super frame adjustment in IEEE 802.15.4 networks is an open research problem. Parameters such as interference and end-to-end delay deadline should be considered during dynamic super frame adjustment. Also, impact of super frame adjustment schemes on node connectivity is an important issue that needs to be studied in length.

6 Conclusion

In this survey, an extensive review of different super-frame adjustment schemes is presented. The requirements of super-frame adjustment using BO and SO in common IEEE 802.15.4 applications are discussed. Also, a brief simulation analysis shows that the fixed BO and SO approach results in degraded performance. Dynamically selecting either BO or SO can partially optimize network performance but both the aforementioned parameters can be adjusted simultaneously for even better results.

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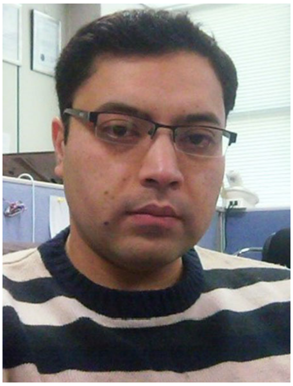

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