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Survey on Beacon-Enabled IEEE 802.15.4 MAC Mechanisms

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Abstract

IEEE 802.15.4 protocol is primarily designed for low rate wireless personal area network (WPAN) with low cost and low power consumption. However, the performance of IEEE 802.15.4 MAC is affected by its limitations such as there is no prioritization in the Guaranteed Time Slot (GTS) allocation procedure. Also, GTS allocations are distributed in first-come-first-serve basis. If allocated devices use GTS slot partially or traffic pattern is not suitable, the wastage of bandwidth will increase. To improve the performance of IEEE 802.15.4 MAC, it is necessary to minimize the power consumption and improve the throughput. In this paper we present the review of existing work of IEEE 802.15.4 MAC and also provide classification of beacon-enabled IEEE 802.15.4 methods based on the performance evaluation. Also, we analyze the work in terms of performance metrics like power consumption, throughput, bandwidth utilization, end-to-end delay, energy efficiency, and quality of service.

Keywords: Wireless Sensor Network (WSN), IEEE 802.15.4, Power consumption, Guaranteed Time Slot (GTS), Energy efficiency, Throughput.

INTRODUCTION

IEEE 802.15 (WPAN) [1] is primarily designed for applications that transmit data over short distances among a private group of participant devices such as PCs, PDAs, wireless printers and storage devices. WPAN requires little or no infrastructure. Wireless personal area network working group (IEEE 802.15) is classified into four task groups: WPAN/Bluetooth (IEEE 802.15.1), coexistence (IEEE 802.15.2) , WPAN high rate (IEEE 802.15.3) and WPAN low rate (IEEE 802.15.4). WPAN low rate (IEEE 802.15.4) is designed for a low data rate up to 250kbps at 2.4GHz band [2]. IEEE 802.15.4 has been deployed in industrial applications, for wireless sensor networks (WSNs) and wireless body area networks (WBANs).

The main objectives of IEEE 802.15.4 protocol are to enable a Low Rate – Wireless Personal Area Network (LR-WPAN) at low cost, with low power consumption among inexpensive devices [2]. The superframe of 802.15.4 has an active and an inactive period, controlled by two parameters – the *Superframe Order (SO)* and *Beacon Order (BO).* Within the active period, devices may transmit data during the Contention Access Period (CAP) or Contention Free Period (CFP). If BO > SO, then the *inactive period* increases. Guaranteed Time Slots (GTSs) allocated during the CFP are used for assigning dedicated time-slots to devices. The devices can use these time slots to transmit periodically generated data without competing for the channel. The number of Guaranteed Time Slots (GTSs) is limited to seven in one *superframe*. In this paper, we review literature which aims to further improve the power consumption [3], [4], throughput [5], [6] , energy efficiency[6],[7], delay [8],[9], and other performance parameters of 802.15.4. We have categorized the different approaches for improving IEEE 802.15.4 protocol according to the mechanism they use for improvement. For example, GTS allocation based schemes [10], [11] provide better GTS bandwidth utilization, improve the throughput, and decrease energy consumption.

The rest of the paper is organized as follows. We present an overview of IEEE 802.15.4 and Zigbee in the next section. Next we classify beacon-enabled IEEE 802.15.4 improvement methods and discuss their performance. After this we analyze the schemes explained in the previous section by considering the performance parameters like power consumption, throughput, bandwidth utilization, end-to-end delay, and energy efficiency. Next we discuss the limitations of the various techniques. We present our concluding remarks in the last section.

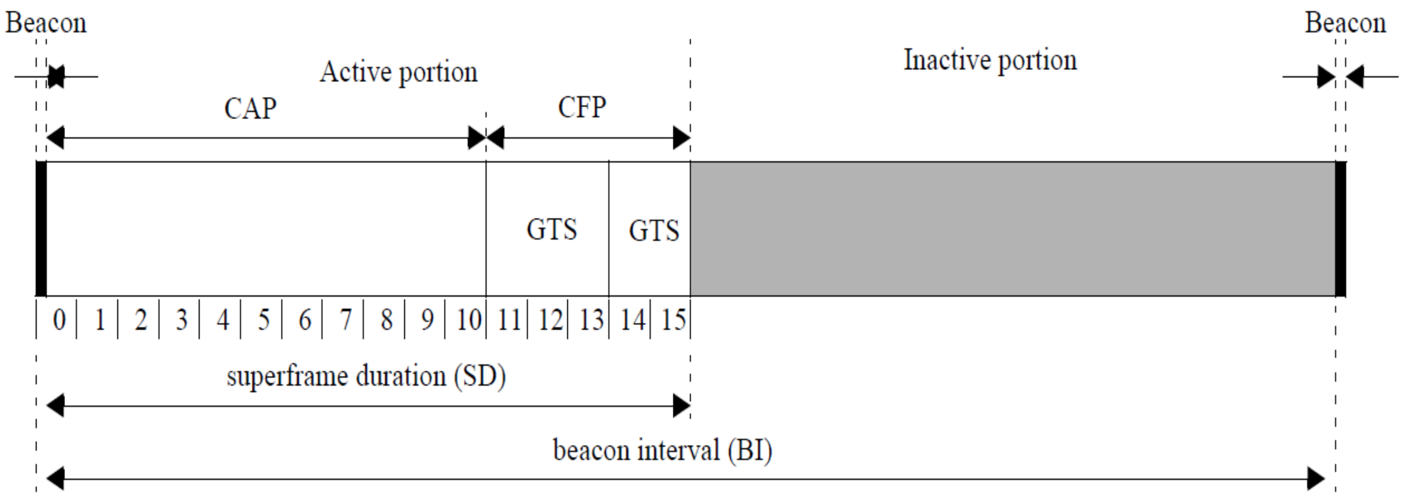

Figure 1: IEEE 802.15.4 Superframe structure

OVERVIEW OF IEEE 802.15.4

In this section we provide an overview of 802.15.4. ZigBee works closely with IEEE 802.15.4 to provide an integrated and complete solution for home automation, industrial control and medical applications. ZigBee technology is developed jointly by ZigBee alliance [12] and the IEEE 802.15.4 group. IEEE 802.15.4 defines the lower layers of the protocol stack, that is, physical layer and MAC sublayer. ZigBee defines the upper layers of the protocol stack from network to application layer.

An 802.15.4 system consists of several components. An 802.15.4 device can act as a *Full Function Device (FFD)* or *Reduced Function Device (RFD)*. FFDs can work in three different modes – as a Personal Area Network (PAN) coordinator, a coordinator, or a device. A Reduced Function Device (RFD) works as an end device and it can only communicate with other FFDs but cannot act as a coordinator. The central controller of the Personal Area Network (PAN) is called the PAN coordinator (PANC). IEEE 802.15.4 protocol uses three network topologies: *star*, *peer-to-peer* and *cluster-tree* topology [2].

In 802.15.4, the medium access is primarily contention based and uses slotted or unslotted CSMA/CA. There are two operational modes, *beacon-enabled* and *non-beacon-enabled*. The beacon-enabled mode is used when support is required for device synchronization and applications with low latency requirements. In the beacon-enabled mode, the PANC sends *beacon frames* periodically after every *Beacon Interval (BI)*. The beacons identify the PAN and help in synchronizing the devices in the PAN. Further, they describe the superframe structure. If synchronization and low latency support is not required then the non-beacon-enabled mode is used. In this paper, we have considered only beacon-enabled mode because this mode is specially suited to provide time guarantees for time sensitive applications.

Figure 1 shows the 802.15.4 MAC-protocol's superframe structure. This superframe consists of an active period (*Superframe Duration (SD)*) and an optional inactive period. The active period is divided into 16 equally sized time slots, during which data transmission is permitted [2].

The active period can be further divided into a *Contention Access Period (CAP)* and an optional *Contention Free Period (CFP)* containing Guaranteed Time Slots (GTSs). The GTSs are allotted to applications to meet application requirements of low latency. PANC allocates GTSs, using the beacon-enabled mode, to the devices that intend to transmit time critical data. The CAP uses slotted CSMA/CA. The superframe structure is defined by two parameters, the *Beacon Order (BO)* and the *Superframe Order (SO)*. BO is used to determine the interval between the beacons or *Beacon Interval (BI)*. The SO is used to determine length of the active portion of the superframe. The values of BO and SO must satisfy the relationship $0<=SO<=BO<=14$. The Beacon Interval (BI) and Superframe Duration (SD) are defined as BI = *a Base Superframe Duration* $*2^{BO}$, and SD = *a Base Superframe Duration* $* 2^{SO}$ for $0<=SO<=14$, where *a Base Superframe Duration (SD)* is the minimum length of the superframe when BO is equal to 0. The IEEE 802.15.4 standard fixes this duration to 960 symbols (1 symbol=4 bits). The duty cycle (DC) for a device is determined by SO and BO and is defined as follows -

$DC=SD/BI$. BI and SD affect the throughput, energy consumption and end-to-end data delivery delay. Smaller duty cycles reduce energy consumption of the nodes, and thus help to improve lifetime of the network, but would lead to a decrease in the network throughput. This is because by reducing duty cycle, packets generated during the inactive period have to wait in the queue for longer period [6].

Each superframe supports up to 7 GTSs. The PANC allocates GTSs to devices when they send a request, if sufficient resources are available in the current superframe. In case sufficient resources are not available, the PANC would defer the GTS allocation, for the device, to the next superframe. Each GTS may contain one or more time slots. Each device may request up to one GTS in the transmit direction and /or

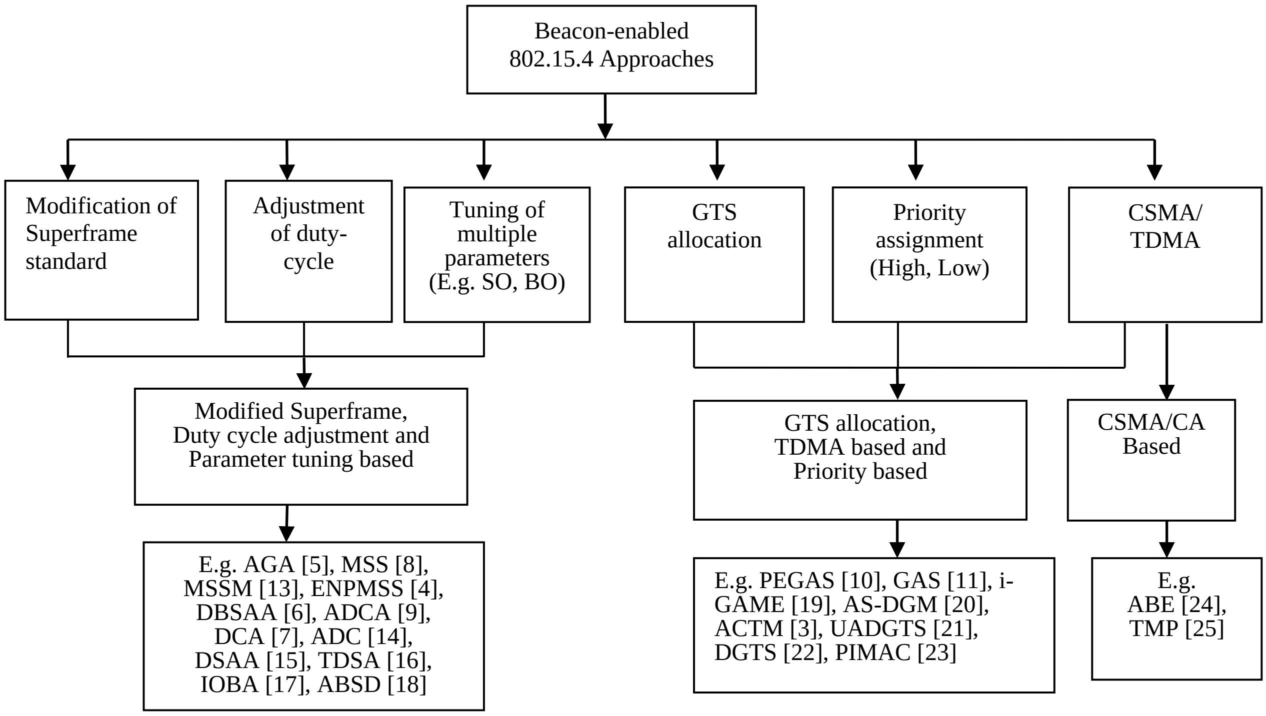

Figure 2: Beacon-enabled IEEE 802.15.4 improvement approaches

one GTS in the receive direction. In case a GTS is not allocated, the device may send the data during the CAP.

In this section, we gave an overview of IEEE 802.15.4 MAC. In the next section, we survey beacon-enabled IEEE 802.15.4 schemes aimed at throughput improvement.

Beacon-Enabled IEEE 802.15.4 Schemes

We classify the schemes which focus on throughput improvement. The schemes that we have surveyed can be categorized as follows: Modification of the standard superframe [5], [8], [13],[4], *adjustment of duty-cycle* [6],[9],[7],[14],[15], *tuning* of multiple parameters[16],[17], [18], GTS allocation[10],[11],[19],[20],

TDMA based [3], priority assignment [21],[22],[23] and CSMA/CA based [24], [25]. Figure 2 shows the classification of the schemes mentioned above.

Modification of the standard superframe is aimed at improving throughput, power consumption and delay. For example, the superframe structure is extended [5] to increase the number of GTSs by increasing the SO value which results in increase in bandwidth utilization. The scheme based on duty cycle minimizes power consumption and improves the throughput of IEEE 802.15.4 MAC protocol. Duty cycle is adjusted by varying SO and BO, that results in decreased energy consumption and power consumption and improved throughput period [6].

Tuning of multiple parameters based scheme precisely selects the values of the parameters like SO, BO, packet size and number of nodes of the IEEE 802.15.4 MAC protocol. By properly selecting SO and BO, superframe is adjusted such that it increases throughput and minimizes energy consumption. GTS allocation based schemes focus on how efficiently GTS can be allocated to the requesting nodes to improve the performance of the IEEE 802.15.4 MAC protocol [10]. CSMA and TDMA based schemes use slotted CSMA/CA and TDMA respectively for improving throughput and energy consumption. The coordinator adaptively divides CAP into slotted CSMA/CA slots and TDMA slots according to node’s data queue state and level of collision detected on the network [3]. Priority based schemes assign priority to the nodes for accessing the medium. It also improves throughput and energy consumption[21].

Schemes Based on Modified Superframe, Duty Cycle Adjustment and Parameter Tuning

In this section, we combine schemes in [5],[8],[4][13], [6],[9],[7],[14],[15],[16],[17],[18] based on modification of superframe standard, duty cycle adjustment and parameter tuning because they consist of common parameters of IEEE 802.15.4 protocol such as SO, BO, GTS, SD, BI, packet size, number of nodes. The modification of superframe structure increases number of GTS, and hence results in high energy efficiency and high bandwidth utilization. These schemes have higher duty cycles and hence result in high throughput, high power consumption and low delay. These schemes provide quality of service (QoS) for time sensitive applications.

In duty-cycle based schemes, the PAN coordinator controls the duty cycle to minimize the packet drop, energy consumption and hence increases the throughput, bandwidth utilization and energy efficiency[9]. However, duty-cycle based schemes result in high end-to-end delay due to large number of nodes transmitting data traffic. These schemes provide support for quality of service for real time applications[14]. Parameter tuning based schemes provide better performance in terms of throughput, energy consumption, power consumption and end-to-end delay by

tuning the multiple parameters like SO, BO ,SD, BI, packet size and number of nodes[17]. These schemes can dynamically adapt heavy traffic. These schemes are application specific and hence they provide good quality of service by enhancing network lifetime.

Yong-Geun *et al.* [5] have proposed the adaptive GTS allocation (AGA) scheme which supports multiple devices and ensures reduction in wastage of channel bandwidth in IEEE 802.15.4 networks. The proposed superframe structure is extended by modifying the necessary fields in beacon frame like ‘Superframe Specification field’, ‘GTS Specification field’, ‘GTS Direction field’, and ‘GTS List field’. In this scheme, the length of one slot (SlotD) in CFP is changed according to the category of SO value given in Table 1[5].

From Table 1, the length of a slot in CFP is divided by a constant value called SlotD into seven slots. If value of SO is in the range 0 to 2, the proposed scheme acts as 802.15.4. If value of SO is greater than 3, the length of one slot in CFP is decreased according to SO value (2*(15-FinalCAPSlot)). The FinalCAPSlot shows the last slot number of CAP period. Using their proposed scheme, it is possible to allocate maximum 127 slots in CFP period and bandwidth can be assigned more accurately. After modifying IEEE 802.15.4 superframe structure and minimizing slot length in CFP period through theoretical computations, the authors have shown that their proposed scheme performs better than general IEEE 802.15.4 in terms of efficient bandwidth allocation. The bandwidth utilization is 25% high as compared to IEEE802.15.4 MAC.

Table 1: Changes of SlotD and the number of slots

Category	**The value of SO**	***SlotD_CFP/ SlotD_CAP***	**Maximum available slot numbers in CFP**
Scope 1	0~2	1	15-*FinalCAPSlot*
Scope 2	3~5	1/2	2*(15-*FinalCAPSlot)*
Scope 3	6~8	1/4	4*(15-*FinalCAPSlot)*
Scope 4	9~11	1/8	8*(15-*FinalCAPSlot)*
Scope 5	12~14	1/16	16*(15-*FinalCAPSlot)*

Pradnya Ghare *et al.*[8] have proposed modifications to the MAC superframe structure of existing 802.15.4 (MSS) in order to improve throughput, power consumption and delay. The total superframe length is adjusted by varying the beacon order (0≤BO≤14) and also the active portion in the superframe is adjusted by varying the superframe order (0≤SO≤14). In IEEE 802.15.4 MAC the total slots in the superframe is 16 and the maximum numbers of GTS slots is 7. Using superframe length, duration of the CAP and the number of GTS slots, the authors have computed the appropriate superframe order (SO). The basic idea is to find the appropriate superframe order (SO) that satisfy the requirements. The authors discover the combinations of superframe lengths and slot duration which could support the Body Area Network (BAN) applications. Authors have considered applications like ECG, EEG etc. For these applications, the total superframe length has to be less than 40ms. Their proposed scheme can support high data rate applications (up to 1 Mbps). Also, their proposed scheme may results in reduction in overhead of header since the MAC header is modified for the BAN applications. The modified MAC frame format consists of various fields like Frame Control, Sequence number, Destination (Dst.), Source (Src.). The modified fields are Dst. Address, Dst. PAN address, Src. PAN address and Src. address. The source address field (Src. address) specifies the sensor (that is placed on the body) sending the data and the source PAN address field (Src. PAN address) helps in identifying the person. Through simulations the authors have shown that the higher duty cycle results in increased throughput and reduction in delay. The modified superframe structure supports increased data rate and increased number of leads for a single BAN. Simulation results show improvement in throughput, power consumption and delay as compared to unslotted CSMA-CA mechanism. Throughput of beacon enabled 802.15.4 MAC is below 50 kbps which is lesser as compared to proposed scheme, whereas throughput of proposed scheme is above 200kbps. Their proposed scheme results in lesser power consumption (above =~1mW) and lesser end-to-end delay (=~50msec) as compared to IEEE 802.15.4 (whereas power consumption for IEEE 802.15.4, above 1.2mW and end-to-end delay is 300msec).

Muhammad Babar Rasheed et al. **[**13] have proposed the modified superframe structure of IEEE 802.15.4 based MAC (MSSM) protocol to address the problems of network lifetime and QoS requirements such as delay, energy consumption and throughput. MSSM also improves energy efficiency. The priority guaranteed CSMA/CA mechanism is used in which different priorities are assigned to body nodes by adjusting the data type and size. A wake-up radio based mechanism to control sleep and active nodes of body sensors are used in order to save energy consumption. A discrete time finite state Markov model is used to find node states. This model provides the probability of body nodes in different states along with their transition probabilities. Using this model the probability of final state could be discovered more precisely. The simulation results shows that MSSM is effective as compared to IEEE 802.15.4 protocol with respect to average energy consumption, delay, throughput, and packet drop ratio. MSSM results 40% higher throughput as compared to IEEE 802.15.4.

Z.A.Khan, et.al.[4] have presented the mechanism for handling emergency data (e.g. Electric Cardio-gram (ECG)) alongwith normal data (e.g. body temperature) and periodic data (e.g. data that a doctor needs after some regular intervals of time like video or audio data) by modifying the superframe structure (ENPMSS). CSMA/CA mechanism is used for normal traffic. Periodic traffic is transmitted through TDMA based time slots. Access point (AP) transmits extra beacon for emergency data. The packet inter-arrival time is included to analyze the energy consumption. Both CSMA/CA and TDMA do not provide any type of emergency data handling mechanism. The type of data is differentiated on the basis of their data rates and packet sizes. Normal data, periodic data and emergency data are assigned normal priority $Data_{normal}$, $Data_{periodic}$ and $Data_{emergency}$ respectively. According to these priorities, nodes and AP take decision during resource allocation and transmission. Body nodes calculates the priority of each data on the basis of equation, Priority= DataType/λt × P_{size} , Where, λt is a traffic generation rate and P_{size} is the length of the data packet generated by the body node. Packet inter-arrival time is also another reason for energy consumption. If inter-arrival time is more than service time, nodes will have to wait due to limited queue size. Hence packet inter-arrival time needs to be adjusted based upon data rate and payload. To avoid queue overflow, service time should be less as compared to packet inter-arrival time. The energy consumption analysis shows that Contention Access Period (CAP) of superframe is not feasible for emergency data due to its extra delay and energy. The proposed protocol performs better as compared to 802.15.4 MAC in terms of throughput, energy consumption and end-to-end delay.

Oliveira *et al.* [6] have introduced the Duty Cycle Self-Adaptation Algorithm (DBSAA) that uses two MAC layer parameters BO and SO for network duty cycle. DBSAA provides more flexibility in duty cycle adaption for increasing the network throughput and decreasing energy consumption and end-to-end delay. DBSAA is designed for 802.15.4 network using beacon-enabled operation mode in a star topology. DBSAA assumes same data rate of all network nodes and does not consider time bound data during event reporting. Also, DBSAA estimates network load based on the number of packets received by the coordinator and number of nodes that sent packets. It is easily performed by the simple measurement made by the coordinator over last N beacon intervals. According to application requirements DBSAA uses two thresholds, the THoccupation and THcollision which describe the traffic behavior. The coordinator maintains the information like number of packets received and number of nodes that sent packets during measurement window. Using this information, the coordinator computes the superframe Occupation Ratio (OR) and Collision Ratio (CR). If OR is smaller than THoccupation, the BO and SO values are not modified. If OR is greater than THoccupation and if SO is smaller than BO, SO is increased which results in increase in packets sent since nodes get more time to send the packets. If CR is less than THcollision, the BO and SO values remains unchanged. Otherwise if SO is smaller than BO, SO is updated. The active period becomes longer and nodes will require less number of slots to send their packets which results in decrease in collisions. Through simulation results the authors have shown that the effect of SO and BO (SO<BO) is better. DBSAA performs better as compared to 802.15.4 MAC and DSAA [15] algorithm in terms of throughput, energy consumption and end-to-end delay. In DBSAA energy drops few seconds earlier (below =~1Joules) than 802.15.4 MAC and DSAA. End-to-end delay is low in DBSAA (below=~1msec) as compared to DSAA (below =~2msec) and IEEE 802.15.4 (below =~4msec).

Hadi Rasouli *et al*. [9] have proposed Adaptive Duty Cycle Algorithm (ADCA) for efficient utilization of network permitting maximum traffic demands. ADCA automatically adjust duty cycle and hence results in minimum energy consumption. ADCA is designed for WSNs using a star topology with a beacon-enabled mode. The coordinator monitors the neighboring nodes and adaptively tunes the BO, SO and BI values which results in increase in network throughput. ADCA adjusts CAP length proportional to the network traffic and ensures decrease in energy consumption and increase in network throughput. The coordinator can increase the network lifetime by appropriately adjusting the duty cycle. The coordinator controls the contention between nodes by determining the collision rates in each superframe and by setting Backoff Exponent (BE). In ADCA, the coordinator selects SO for each superframe based on idle time, throughput of CAP and queue state of nodes. The algorithm works in three cases. In first case, the idle time length is more than half of the CAP length in current superframe. Hence coordinator decrements SO by one unit and selects it as the SO for the next superframe. Due to this, CAP size for the next superframe is halved. It controls the collision rate of the nodes that occurs in each superframe. In the second case, when the idle time length is less than half of the CAP length, then coordinator compares number of received packets and number of awaiting packets during the CAP. If the awaiting packets at PAN coordinator are more than received packets then SO is increased by one. If SO=BO, coordinator decreases the BE value and nodes will be able to send their packets more contentiously and speedy. This prevents dropout of packets and decreases the delay. In case three, when the remained pending packets are less than the numPkt value based on the nodes queueState array, coordinator selects the SO of current superframe as the SO of the next superframe. The numPkt is the maximum number of sent packets in idle time based on CAP Throughput. The queueState array of a node consists of number of pending packets at the end of each cap. For selection of SO, the coordinator compares collision rate with two different thresholds, UPPER and LOWER, to increase the throughput of the network. The UPPER and LOWER thresholds are maximum and minimum of acceptable collision rates in the network. If the collision rate is more than UPPER rate, BE is needed to be increased in order to decrease the collision. If the collision rate is less than LOWER threshold, BE is decreased and contention among the nodes is increased. The coordinator send the values of SO and BE to all nodes. Through simulation results the authors have shown that with respect to energy consumption, network life time and throughput, ADCA performs better as compared to AAOD [9], DSAA [15], DCA [7], AMPE [9] and IEEE 802.15.4. In ADCA, average of per packet energy consumption decreases 50%, 34%, 34%, 31% and 45% as compared to AAOD, DSAA, DCA, AMPE and IEEE 802.15.4 respectively. In ADCA, throughput increases by 81.5%, 39.7%, 52.9%.39.9% and 78.6% as compared to AAOD, DSAA, DCA, AMPE and IEEE 802.15.4 respectively. In ADCA [9], bandwidth utilization is 43.3% high and delay is low (below 1msec) as compared to IEEE 802.15.4.

Joseph Jeon *et al.*[7] have proposed Duty-cycle Adaption algorithm (DCA) in which coordinator controls the duty cycle by keeping BO constant and by setting SO adaptively. The PAN coordinator adapts the value of SO based on different metrics including queue size, energy consumption and data rate. Their proposed algorithm is composed of MAC status index (MSID) and a SO decision algorithm at the coordinator. Buffer occupancy and queuing delay are combined to represent MSID in 8 levels. Buffer occupancy is divided into 4 layers and queuing delay is into 3 levels. Each end device has a limited queue size, hence buffer occupancy is important parameter to prevent the packet drop. The end device enters into sleep mode which causes delay for packet transmission called sleep delay. Increase in MSID indicates that the packets are stacked and network is heavily loaded. The coordinator decides the SO value by the delivered MSID and other parameters collected during an active duration. The reserved 7^{th} to 9^{th} bits from the MAC are used for MSID field. The coordinator determines the SO using MSID, number of end devices and number of packets received. If small BO is used, inactive portion becomes small and large number of packets will be transmitted which results in increase in energy consumption. When SO value increases, the packet drop reduces. In DCA [8], the packet drop is low for the SO=0 or SO=1. Through simulation results the authors have shown that DCA controls duty cycle which results in reduction in packet drop and increase in energy efficiency. In DCA throughput is low (=~1Kbps), energy consumption is low (below=~0.2Joules) and end-to-end delay is low (above=~0.2sec) as compared to IEEE 802.15.4.

Shashwat Pathak. *et al.* [14] has investigated the energy optimization in the beacon enabled mode of IEEE 802.15.4. Adjustable duty cycle (ADC) operation is performed by setting two system parameters, Superframe Order (SO) and Beacon Order (BO). The authors have proposed a tele-cardiac patient monitoring system in which they monitored the ECG of cardiac patients. ECG signal is measured by battery operated ECG sensors placed on patient’s body. All the sensors send data to a main nurse’s Personal Digital Assistant (PDA) and then to Doctor’s PDA for monitoring in case of emergency. For faster connection between sensors and nurse’s PDA and also to connect Doctor’s PDA to nurse’s PDA, ZigBee is used. They have considered a typical 200m*200m hospital scenario in which the ECG sensors are connected to the FFD device called nurse’s PDA. The PDA or the sink nodes are connected to a central node (Doctor’s PDA) which receives all the data from the nurse’s PDA. In this scenario, the parameters being varied is Superframe duty cycle which is varied by changing Superframe order (SO) and Beacon order (BO). The optimal duty cycle is carried out by varying load and packet rates. The authors analyzed the energy consumption in transmit mode, receive mode and idle mode. Simulation results show that at lower duty cycle, throughput increases. The average end-to-end delay in ECG transmission increases with increase in duty cycle. The energy consumed in transmits mode increases with increase in duty cycle. The energy consumed in receive mode is less for selected duty cycles. The lower duty cycle performance is better as compared to higher duty cycle and it can further increase the lifetime of the network. The proposed mechanism performs better as compared to 802.15.4 MAC protocol in terms of energy consumption and end-to-end delay.

Lee *et al.* [15] have introduced the dynamic superframe adjustment (DSAA) that adjusts only the SD duration by varying the SO and keeping BO fixed. During high traffic load, the insufficient active period results in decrease in transmission opportunities of devices and increase in collision. DSAA is designed to solve this problem that dynamically adjusts the duty cycle of the superframe according to the channel opportunity and collision ratio observed by the coordinator. The coordinator calculates the superframe occupation and collision rate using number of nodes, the packet length, time required to transmit a packet, number of nodes transmitting packets and number of nodes unsuccessfully transmitting packets. The coordinator compares these values to the threshold of superframe occupation and threshold of collision. Accordingly, the length of the active period for next superframe is adjusted by the coordinator. DSAA can dynamically adjust the value of the SO according to the traffic load of the network. Through simulation results the authors have shown that with respect to goodput (goodput is the rate at which useful data traverses a link), delay and power consumption, DSAA performs better as compared to the IEEE 802.15.4. In DSAA, goodput is better (above 50Kbps) as compared to ECAP [26] (above 25Kbps) and IEEE 802.15.4 (above 25Kbps). Energy consumption in DSAA is lower (below 0.004Joules) than ECAP (above 0.004Joules) and IEEE 802.15.4 (0.005Joules).

Farhad *et al*. [16] have proposed the Traffic Aware Dynamic Superframe Adaption algorithm (TDSA) that adjusts superframe through Beacon Order (BO) and Superframe Order (SO) for increasing throughput and decreasing latency and energy consumption. The algorithm has been designed for star topology in beacon enabled mode of IEEE 802.15.4 network. TDSA consider only CAP period and assume that GTS has not used. TDSA also assume that the PAN coordinator is aware about the nature of traffic delivered by different sensors and different events generated by them. Superframe adjustment refers to the adjustment of both BO and SO for selection of beacon interval and active portion within a beacon interval respectively. The PAN coordinator calculates the expected duration of the active portion based on the data rate requirement of traffic flow. The first step in TDSA is to estimate SO (SO_{Exp}) after the expiry for every BI. SO_{Exp} is the expected length of superframe duration (SD) for next beacon interval (BI). It depends on the required throughput and is calculated on the number of PAN source members and their data rates.Through simulation results the authors have shown that with respect to throughput, energy consumption, packet loss and end-to-end latency, TDSA performs better as compared to IEEE 802.15.4. Average throughput of TDSA is better (above 90kbps) as compared to AMPE (below 85kbps), AAOD (below 90kbps) and IEEE 802.15.4 (below 50kbps). Average energy consumption is low for TDSA (below 0.5%) and IEEE 802.5.4 (below 0.4%) , where as it is high for AMPE (above 0.7%) and, AAOD (above 0.7%). The end-to-end delay of TDSA is low (below 0.3msec) as compared to IEEE 802.15.4 (above 6msec).

Bo Gao *et al*. [17] have proposed an individual beacon order adaption algorithm (IBOA) for improving performance of IEEE 802.15.4 networks. In IBOA, SO is set to constant value and BO is assigned for each node individually. The coordinator calculates beacon interval (BI) and duty cycle of each node using current value of BO. Both the beacon interval and duty cycle of each node can be changed by BO at the same time. Therefore active portions of the any two different nodes may not begin at the same time and hence reduces competition for accessing the channel. IBOA individually adapts the beacon interval and duty cycle of each node which results in reduction in power consumption, ensures end-to-end delay requirements and increase in throughput. In IOBA, power consumption is high (above 40Mw), throughput is high (above 70 packets/sec) and delay is high (above 5sec) as compared to IEEE 802.15.4.

Thien D Nguyen *et al*. [18] have presented an energy harvesting model to show effectiveness of human body motion based energy. They have proposed an adaptable duty cycle adjustment algorithm ABSD (Adaptive Beacon Order, Superframe Order and Duty cycle) to prolong a WBAN node battery lifetime. Algorithm allows us to adapt the value of duty cycle according to offered load conditions by simultaneously adjusting BO and SO values. By combining these two approaches, the authors have resolved the issue of energy efficiency in an IEEE802.15.4 WBAN under variable traffic conditions. The authors performed their experiments on OPNET as well as MATLAB for analyzing performance of data in WBAN. OPNET based discrete event model was developed to measure the performance of ABSD packet transmission technique. MATLAB model is used to compute battery lifetime by linking energy profile of WBAN nodes with energy scavenging model. Their proposed mechanism performs better in terms of energy efficiency as compared to IEEE802.15.4 protocol.

Schemes based on GTS Allocation, TDMA based and Priority Assignment

In this section we explain the schemes based on TDMA, GTS allocation and Priority assignment. In GTS allocation schemes, the coordinator allocates GTS dynamically to the requested nodes and results in high bandwidth utilization and high throughput. These schemes result in low energy consumption, low power consumption and low end-to-end delay because packet retransmission in CAP is reduced. Hence, they provide support for better quality of service for real time applications. TDMA based schemes can be mainly used for applications with bursty traffic conditions. In these schemes, the part of contention access period (CAP) is dynamically assigned to TDMA for GTS slot allocation. This increases contention free period (CFP) and more number of slots is available for GTS allocation. Therefore large number of packets can be transmitted. Hence, TDMA based schemes result in high bandwidth utilization, high throughput, low energy consumption and low end-to-end delay. In priority assignment schemes, priority is assigned to nodes for accessing the medium. These schemes result in reduction in energy consumption and increase in throughput. However, these schemes require extra power for processing. In these schemes the coordinator dynamically assigns GTS to the devices based on the priority in each superframe and hence results in high throughput and high energy efficiency. These schemes can dynamically adapt to traffic changes and result in low end-to-end delay that provides support for better quality of service for real time applications.

Harun *et al.* [10] have proposed the Partitioned GTS Allocation Scheme (PEGAS) for improving GTS bandwidth utilization, throughput, energy efficiency and latency for IEEE 802.15.4 networks. PEGAS addresses the issues of unsuitable traffic pattern and wastage of bandwidth. The main objective of PEGAS is to decide the precise time for the starting time (GTSstart), the end of the GTS(GTSend) and GTS length (GTSlength) allocation for requested devices by considering the data packet length, SO value and packet arrival rate. Coordinator calculates time of one slot duration, time to transmit one data packet, time to transmit data using packet arrival rate and number of requested slots for each GTS of IEEE 802.15.4 by each device. Coordinator calculates values of GTSend and GTSlength using PEGAS algorithm. In PEGAS, 16^{th} slot is partitioned into smaller slots forming CFP and CAP. In this, seven slots are assigned to CFP and remaining slots are assigned to CAP. The requesting nodes will get one slot out of 16^{th} slot. In case where number of nodes is greater than 7, the nodes for which GTS is not allocated, can transmit data packets in CAP period. PEGAS results in increased in CAP duration and decreased in CFP period which eventually increases bandwidth utilization. Using simulation results the authors have shown that the performance of PEGAS is better than IEEE 802.15.4, with respect to throughput, energy efficiency and latency. In PEGAS [10] power consumption is low (about 3mW), throughput is high (above 100kbps), and energy consumption is low (below 200 micro joule/packet) as compared to IEEE 802.15.4.

Shrestha *et al.* [11] have proposed GTS Allocation Scheme (GAS) for improving reliability and bandwidth utilization in wireless body area networks. It is based on optimization problem to minimize the bandwidth requirements. An optimization problem is the problem of finding the best solution from all feasible solutions. In traditional IEEE 802.15.4 MAC, GTS is allocated in first-come-first-serve basis. It results in wastage of bandwidth due to asymmetric traffic conditions of different sensor nodes. Authors have defined a priority computation method to solve this problem that depends on the packet generation rates of nodes. The nodes check their buffers contents to set their priorities. The nodes use this information with GTS allocation requests and send it to the coordinator. During CAP period, the coordinator collects all GTS requests. GTS allocation is optimized using knapsack problem. A knapsack problem is formulated to obtain optimal GTS allocation for different devices. The coordinator uses a fractional knapsack optimization problem to allocate GTSs according to priority of the nodes. Their proposed scheme performs better as compared to IEEE 802.15.4 with respect to average packet delivery ratio 0.9) above, end to end delay (=~ 1sec) and packet discard rate (0.05).

Koubaa *et al.*[19] have proposed an implicit GTS allocation scheme (i-GAME) to improve the GTS utilization. This scheme is used to overcome the drawbacks of GTS allocation mechanism in beacon-enabled IEEE 802.15.4. In traditional IEEE 802.15.4, a single GTS is assigned to a requesting node. i-GAME scheme allows multiple nodes to share GTS in a round-robin fashion. The time slots of a shared GTS among several nodes are dynamically allocated to different nodes in each superframe according to a given schedule, which is formed by PAN coordinator. GTS allocation mechanism is based on the traffic of the requesting nodes, their delay requirements and available GTS resources. Nodes send their traffic specifications like maximum amount of bits transmitted, arrival rate and delay requirements to the PAN coordinator. The coordinator uses this information to run admission control algorithm. The algorithm computes the available GTS resources and responds accordingly. Using simulation results the authors have shown that with respect to efficient bandwidth utilization, i-GAME performs better as compared to standard GTS allocation in IEEE 802.15.4. In i-GAME, bandwidth utilization is high (about ~97%) and end-to-end-delay is low (below ~250msec) as compared to IEEE 802.15.4.

Marwa Salayma *et al.* [20] have presented two IEEE 802.15.4 TDMA based techniques namely adaptive sleep IEEE802.15.4 MAC and dynamic GTS IEEE802.15.4 MAC (AS-DGM) to improve WBAN reliability and energy efficiency. In the first technique nodes are allowed to avoid channel deep fade by distributing adaptively their sleep period during their active period according to their channel status. In the second technique, time slots are allocated to nodes dynamically according to their requirements that depend on their link's status. In adaptive sleep IEEE802.15.4 MAC, TDMA based free channel access mechanism is used in which GTS(s) are offered in the contention free period (CFP) which follows CAP(Contention Access Period) in the active period. The nodes send GTS request packets to PAN coordinator (PANc). After receiving this request, PANc acknowledges the node and offers that node a number of GTS(s) according to GTS request. After this GTS request, nodes are scheduled to access the channel. As per the schedule, the node will wake up during its GTS(s) period and try to transmit its packets. If the node fails to receive acknowledgment frame from the PANc, it indicates that its link with the PANc suffers from a deep fade. It will not perform packet retransmission and will shutdown its transceiver if the inactive period is enabled. The node will continue sleeping until the current BI finishes. The node will wake up when the current BI finishes in order to receive the next beacon frame. The other nodes will use the channel according to the schedule. In the second technique of dynamic GTS IEEE802.15.4 MAC, the time slot allocation is dynamic according to nodes' needs. In this assumption is that, WBAN consists of 5 clients/nodes. Each node is allocated 3 time slots when network is created. Those nodes that have slept adaptively during the current BI due to fading can be given extra slots in the next BI. Therefore, they can get enough time to transmit the packets that have been stored in their buffer. These extra slots can be allocated from other nodes whose links have not suffered from fading in the current BI. This technique is suitable for high traffic load networks and emergencies. The nodes having critical or emergent data should be assigned more slots than other nodes with normal data by considering fading in the channel. Their proposed dynamic GTS improves performance of nodes. It consumes much less energy as compared to adaptive sleep and traditional IEEE 802.15.4 MAC at moderate, high and very high data rates.

Gilani *et al.* [3] have proposed an adaptive CSMA/TDMA hybrid MAC (ACTM) protocol to improve throughput and the energy consumption of IEEE 802.15.4 MAC using star topology in a beacon enabled mode. Using simulation results the authors have shown that CSMA-CA does not perform well under high traffic loads. Hence, they introduced the concept of time division multiple access (TDMA) in the CAP of the superframe. The main idea is to add a dynamic TDMA period into CAP of 802.15.4 standard. The coordinator adaptively divides the CAP into slotted CSMA-CA slots and TDMA slots according to nodes' data queue state and level of collisions detected on the network. In GTS specification field, the three bits are GTS Descriptor Count (0-2), the four reserved bits (3-6) represents number of slots belonging to TDMA period. In this way upto 16 slots can be used for TDMA slots. The queue state information of the network nodes can be acquired by using reserved bits in the transmitted frames. The beacon frame GTS descriptor and reserved bits are modified to assign TDMA slots to network nodes. The coordinator assigns TDMA slots to network nodes. It resolves the two main issues of TDMA-based protocols: i) The coordination of nodes and ii) The under-utilization problem in TDMA networks in heavy traffic loads. Number of nodes that take part in the contention can be controlled using TDMA slots in the CAP which results in reduction in collisions, reduction in energy consumption of nodes and increase in throughput. The network coordinator uses greedy algorithm to determine the border between CSMA/CA and TDMA periods. Using simulation results the authors have shown that with respect to throughput, energy consumption and end-to-end delay their proposed protocol performs better as compared to 802.15.4 MAC. In their proposed schemes, throughput is 3.7 times higher, energy consumption is 38% to 70% low and delay is low (below 5sec) as compared to IEEE 802.15.4 MAC protocol.

Hyung Cho *et al*.[21] have introduced utilization-aware dynamic GTS allocation scheme (UADGTS) to improve the throughput of overall network and reduce latency for data transmission. PAN coordinator manages priority of each device. It dynamically assigns GTS to devices based on the priority in each superframe. The authors have introduced *state and utilization factor* for computing priority for each device. The utilization factor is used for calculation of priority. PAN coordinator calculates the value of the utilization factor as the ratio of the amount of data that the device can transmit to PAN coordinator during the assigned GTS in n^{th} superframe to the amount of maximum data that the device can transmit to the PAN coordinator using assigned GTS in a superframe. In every superframe, PAN coordinator dynamically allocates

GTSs to devices in descending order of their priorities that have been calculated before the starting time of the subsequent superframe. In the subsequent superframe, the top seven devices will be assigned GTSs. The state is decided according to property of GTS usage and is used for managements of priority. The PAN coordinator classifies devices based on three states namely non-GTS, GTS-occupation, and GTS-desire states and maintains states of its associated devices. For each state there are three different priority management methods. In non-GTS state, the PAN coordinator does not maintain priority for the device. In GTS-occupation state, PAN coordinator calculates the priority of the device before every starting time of a superframe. In GTS-desire state, PAN coordinator keeps priority of the device for assigning GTS. Through simulation results the authors have shown that with respect to throughput and queuing delay, their proposed scheme performs better as compared to IEEE 802.15.4. Using their scheme, throughput is higher (above =~9Kbps) than IEEE 802.15.4 (above =~6Kbps) and average waiting time is lower (below=~100sec) than IEEE 802.15.4 (above 800sec).

Tuomas Paso *et al.* [22] have introduced a novel dynamic guaranteed time slot (DGTS) allocation scheme that enables effective utilization of the GTS slots in the IEEE 802.15.4 MAC protocol. DGTS addresses the following issues of IEEE 802.15.4 MAC: the maximum number of GTSs is limited to seven in one superframe. GTS allocation without prioritization and first-come-first-serve basis. DGTS adds three additional fields: Type of Service, GTS Buffer Length and Highest Type of Service to the IEEE 802.15.4 MAC frame. The PAN coordinator maintains the list of the GTS buffer lengths of the end devices located inside the PAN. The PAN coordinator updates the list of GTS buffer length after receiving data packet using the information extracted from packet's header. The PAN coordinator checks the list before sending a beacon and executes the DGTS allocation scheme in two phases. In phase 1, the PAN coordinator allocates the GTS slots based on the GTS buffer lengths of the end devices. The end device having largest GTS buffer length is identified and then PAN coordinator calculates the number of GTS slots to be allocated to an end device. In phase 2, the PAN coordinator first checks the value of the Highest Type of Service field from the packets headers. When an end device could not get a GTS slot in phase 1, but it has a packet with a highest priority than packets of other end devices, then PAN coordinator allocates one GTS slot to that respective end device. DGTS guarantees immediate channel access to the highest priority traffic. More number of devices get GTS slot. Using simulation results the authors have shown that throughput is higher (above=~7Kbps) than IEEE 802.15.4 (above=~5Kbps) and delay is higher (above=~ 0.5 sec) than IEEE 802.15.4(above =~0.05sec).

Jardosh *et al.*[23] have introduced explicit priority based channel access mechanism (PIMAC) for beacon enable mode of 802.15.4 MAC. Their proposed mechanism categorizes the nodes as normal nodes and critical nodes. The authors define the normal nodes as the nodes which can transmit the routine information like information of environment monitoring applications and allow delay at certain extent. The authors define critical nodes as the nodes which transmit important information for example detection of monitored phenomenon such as an intruder, high temperature conditions to the coordinator, etc. The critical nodes are considered as high-priority nodes and normal nodes are considered as low-priority nodes. The coordinator includes the priority information in the primary beacon and periodically broadcasts it to all the nodes. The normal nodes are not allowed to contend for the channel during the CAP and hence results in reduction in competition for channel. Hence, using their proposed mechanism, the traffic priority is maintained by giving preference to the critical traffic over regular traffic. Simulation results show that their proposed scheme has higher packet delivery count (below=~3500) as compared to IEEE 802.15.4 (below=~2500) and energy consumption is lower (0.000015Joules) as compared to IEEE 802.15.4(0.00002Joules).

Schemes based on CSMA/CA

In this section we explain the schemes based on CSMA/CA.

Nazim Abdeddaim *et al.*[24] have proposed the model that addresses the issue of optimizing the operation of IEEE 802.15.4 networks. Their proposed model uses the Idle Sense access method for 802.11 and 802.15.4 slotted CSMA/CA using bursty nature of the traffic. By combining these two approaches the authors have formed a model of IEEE 802.15.4 and proposed Adapting contention window (ABE) mechanism. The model is validated and used to derive ABE that adjusts the contention window according to the function of active nodes and varying traffic patterns. The suitable values of SO and BO are considered for simulation. In ABE, the PAN coordinators derive the load of access channel and distribute the values of contention window to the associated devices. Using simulation results, the authors have shown that ABE results in high throughput (above 16Kbps), high packet delivery ratio (0.85) and low end-to-end delay (below 2sec) as compared to standard IEEE 802.15.4 MAC.

Muhammad Sajjad Akbar *et al.* [25] have proposed a tele-medicine protocol (TMP) under IEEE 802.15.4 slotted CSMA/CA with beacon enabled mode for remote patient monitoring systems. TMP combines two optimizations methods namely MAC layer parameter tunning optimization and duty cycle optimization. Their approach consists of three steps. In the first step, network traffic and its transmission time are estimated by considering a network with six to ten biomedical sensor nodes. The idea is to estimate the total required time for the transmission of data of 100kbps. This time is considered to set the superframe duration. In the second step, the channel access and collision probabilities are calculated. End-to-end delay is computed for the slotted CSMA/CA to make TMP protocol reliable with limited latency. It also considers a reasonable reliability in terms of retransmission and channel access attempts. The energy consumption of a node depends on the selection of the duty cycle value. In the third step, the optimized duty cycle value is calculated by considering the superframe duration value of the system. The assumed that the value of the CFP is zero that means CAP represents the complete active period. Authors have used the MAC layer parameter optimization approach for tunning the MAC layer parameter according to delay and reliability needs of remote patient monitoring systems. The authors compute multiple combinations of performance parameters, backoff exponent (BE) macCSMABackoff and macMaxFrameRetries for slotted CSMA/CA that can fulfill the requirements of medical applications in terms of limited delay(less than 250ms) and reasonable reliability. In TMP delay is reduced by 91%, 87%, 75%, 78%, and 63% compared to AAOD [25], AMPE [25], ADCA [7], DSAA [10], DCA [8] and IEEE 802.15.4 respectively. TMP provides better performance for energy consumption (2.3 Joules/sec) as compared to other protocols.

In this section we have discussed classification of Beacon-Enabled IEEE 802.15.4 schemes based on their performance evaluation. In the next section we present the analysis of the schemes discussed in section 3.

Analysis of Beacon-Enabled IEEE 802.15.4 Schemes

In this section, we provide the analysis of the beacon-enabled IEEE 802.15.4 schemes using various parameters like power consumption, bandwidth utilization, throughput, energy efficiency, end-to-end delay and Quality of Service (QoS). Table 2 shows the analysis of schemes discussed in section 3.

Below Table 2 shows comparison of various beacon enabled schemes of 802.15.4 with 802.15.4 MAC protocol.

Table 2: Comparative analysis of the existing beacon-enabled IEEE 802.15.4 schemes with IEEE 802.15.4 protocol

Mechanism	Power consumption	Bandwidth utilization	Throughput	Energy Consumption	End-to-End delay	Applications
AGA [5]	High	25% high	High	Low	Low	Medical treatment like ECG & EEG.
MSS [8]	Low above=~1mW	High High	High, more than 200 Kbps	Low Low	Low below =~50 msec	Medical purpose e.g. ECG and EEG.
MSSM [13]	High	High	40% High	High	High	Medical treatment
ENPMS [4]	Low	High	High	High	Low	Handling normal, periodic data.and emergency data
DBSAA [6]	Low	High	High upto =~ 250Kbps	Low below =~Joules	Low below =~1 msec	Smart homes & environmental monitoring
ADCA [9]	Low	43.3% High	78.6% High	Low decreases to 45%	Low below =~1 msec	Highly variable traffic conditions
DCA [7]	Low	Low	Low =~1Kbps	Low below =~Joules	Low above =~0.2 sec	Variable network traffic load
ADC [14]	High	High	Low	Low	High	Wireless telemonitoring scenario of cardiac patients
DSAA [15]	Low =~31.3mW	High	NA	Smaller above =~0.004Joules	Low above =~400msec	Networks having high traffic load
TDSA [16]	High	High	High above =~90 Kbps	Low above =~0.% Joules	Low below =~0.3 sec	Variable traffic load
IOBA [17]	High above =~ 40mW	High	High above =~70 packets/sec	NA	High above =~5sec	Low power WSN applications
ABSD [18]	High	Low	NA	Low	Low	Patient monitoring in WBAN
PEGAS [10]	Low =~ 3.0mW	High	High above =~100Kbps	Low below =~200 microjoule/packet	NA	Real time applications

Table 2 Continued…

Mechanism	Power consumption	Bandwidth utilization	Throughput	Energy Consumption	End-to-End delay	Applications
GAS [11]	Low	High	High	NA	=~ 1sec	Data collection in a WBAN sensor networks
i-GAME [19]	Low	High about =~97%	NA	NA	Low below =~250 ms	Real time applications
AS-DGM [20]	Low	High	NA	Low	High	WBAN for E-Health systems
ACTM [3]	High	High	2.3 times High	Low	Low	Real time applications
UADGTS [21]	High	High	High =~ above 9Kbps	NA	Low=~ below 100sec	Variable traffic conditions
DGTS [22]	Low	High	High=~ above 7Kbps	NA	High above=~ 0.5sec	Biomedical sensor applications
PIMAC [23]	Low	High	NA	Low below 0.000015 Joules	Low	Mission critical applications
ABE [24]	Low	High	High above =~16Kbps	NA	Low below=~ 2 sec	Networks with bursty traffic conditions
TMP [25]	Low	High	High	Low	Low	Remote monitoring of medical field

DISCUSSION AND FUTURE WORK

In this section we discuss the limitations of Beacon-Enabled IEEE 802.15.4 mechanisms.

In the modification of Superframe standard schemes in [5],[8],[4][13] the authors have used SO, BO and GTS parameters. The PAN coordinator needs to modify original superframe structure by fine-tuning values of parameters such as SO, BO and GTS. For e.g. the superframe length is adjusted by varying the beacon order (0≤BO≤14) and the active portion in the superframe is increased by varying the superframe order (0≤SO≤14) [8]. In the future work, by using proper design of experiments methods and fine-tuning the parameters of IEEE 802.15.4, accurate parameter values can be determined.

The PAN coordinator needs to perform extra task of processing and analysis due to heavy traffic. For e.g. in DSAA[15]and TDSA[17] as the traffic conditions increases it causes a burden on the PAN coordinator for processing and analysis. In the future work, the algorithms in DSAA[15]and TDSA[17] needs to be modified for multimedia applications. This is because in multimedia applications there is very high load on PAN coordinator.

In GTS allocation schemes [10], [11], [19], [20], there is no proper allocations of GTS. For e.g. in PEGAS [10], the authors have considered SO, GTS and data packet length parameters. PAN coordinator does not use prioritization concept in the GTS allocation procedure. Therefore GTS allocation is not done properly. In the future work, this scheme needs to be designed with fair bandwidth allocation and hence proper utilization of GTS.

In priority based schemes UADGTS [21], DGTS[22] and IEEE 802.15.4 [23], the authors have considered GTS and the number of nodes. In these schemes the PAN coordinator computes priorities of the nodes. This results in processing overhead on PAN coordinator. In the future, a simplified algorithm for scheduling of GTS will reduce the overhead on PAN coordinator.

CONCLUSIONS

In this paper we have provided the classification and discussion of Beacon-Enabled IEEE 802.15.4 methods based on their performance evaluation. We have classified the schemes based on modification of superframe standard, duty-cycle based, tuning the parameters based, GTS allocation scheme based, CSMA/TDMA based and priority based. Also, we have analyzed the performance of these schemes by taking into account the performance metrics like power consumption, throughput, bandwidth utilization, end-to-end delay, energy efficiency and quality of service. The GTS allocation based schemes, priority-based schemes and CSMA/TDMA based schemes provide better quality of service. This is because in GTS allocation based schemes the number of GTS allocations is increased upto 127 slots. These schemes can be used for time sensitive applications. The priority-based schemes assign priority to the important information for example detection of monitored phenomenon such as an intruder, over regular information like information of environment monitoring applications. The CSMA/TDMA based schemes dynamically assigns the part of contention access period to TDMA for GTS slot allocation. These schemes increase the throughput and reduce the energy consumption of IEEE 802.15.4 MAC. These schemes are suitable for heavy traffic loads using TDMA. Further investigations are needed to improve the performance of IEEE 802.15.4 protocol, by way of GTS priority, scheduling algorithms, appropriate design of experiments for determining correct parameter setting.

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