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OGMAD: Optimal GTS-Allocation Mechanism for Adaptive Data Requirements in IEEE 802.15.4 Based Internet of Things

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ABSTRACT Future Internet of Things (IoT) will utilize IEEE 802.15.4 based low data rate communication for various applications. In the IEEE 802.15.4 standard, nodes send data to their Personal Area Network (PAN) coordinator using the Guaranteed Time Slot (GTS). The standard does not meet the adaptive data requirements of GTS requesting nodes in an efficient manner. If requesting GTSs in an active period are more or less than the available limit, either the requested nodes will not be entertained or GTSs remain underutilized. Consequently, it may cause unnecessary delay or poor GTS utilization. In this paper, an Optimal GTS allocation Mechanism for Adaptive Duty cycle (OGMAD) is proposed that adapts the active period of the superframe in accordance with the requested data. *OGMAD* also reduces GTS size to improve link utilization as well as accommodate more GTS requesting nodes. Simulation results verify that *OGMAD* improves link utilization, reduces network delay and offers more nodes to transmit their data as compared to the standard.

INDEX TERMS IEEE 802.15.4, Internet of things, wireless sensor networks, MAC protocol.

I. INTRODUCTION

Internet of Things (IoT) is emerging rapidly during the current decade due to its wide range of diverse applications such as traffic management, smart agriculture, and home automation [1]–[3]. Also, IoT is used for monitoring, tracking, and calibrating industrial instruments to enable them for mission-critical applications [4], [5]. These critical applications require high throughput, low power consumption and guaranteed data delivery with a permitted latency [6]. Most of these mission-critical applications do not require a high bit rate. Physical and Medium Access Control (MAC) layers are under prime attention to meet these IoT challenges.

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IoT uses Wireless Sensor Networks (WSNs) as one of its core components [7], [8]. This is why the MAC protocols designed for WSNs are equally applicable for IoT applications. A WSN comprises of several wireless sensor nodes with limited energy resources. Multiple MAC protocols are designed for WSNs. However, some MAC protocols such as LoRaWAN [10], and Symphony Link [10] are specifically designed for IoT.

LoRaWAN is designed for low powered devices and specifies three device types including Class A, Class B, and Class C. Class A devices support bi-directional communication between the gateway and the device by using an ALOHA based algorithm and does not allow guaranteed success. Class B devices add scheduling in the Class A devices by using the time-synchronization beacon transmitted by the gateway. These devices open their receive windows periodically that increases network latency. In Class C, network latency is reduced by opening the receive windows of devices all the time except during transmission. However, this consumes more energy as compared to the previous two classes. Symphony Link is a synchronous protocol and its performance degrades and does not meet the mission-critical applications, because it employs a very restrictive environment. IEEE developed a standard for a low rate and low power WPAN and known as IEEE 802.15.4 [11] by offering a duty cycle from less than 0.1% to 100%.

IEEE 802.15.4 standard operates on the physical and MAC layer and is preferred for such wireless networks, that require a low data rate with less power consumption such as WSNs. A well known Zigbee devices use IEEE 802.15.4 standard for their Physical and MAC layers. The standard operates on 868 MHz, 915 MHz, and 2400 MHz frequency bands. The standard offers beacon-enabled mode and allows nodes to send their data by following contention-based or contention-free manners. During beacon-enabled mode, a superframe structure is introduced that includes the Contention Access Period (CAP) and Contention Free Period (CFP). Nodes are preferred to transmit their data during CFP to avoid congestion and to maintain Quality of Service (QoS). The standard is also used by many low rate and low power applications due to its flexible duty cycle.

The beacon-enabled mode of the standard is also attracted by many researchers due to its high demand in a variety of applications. The researchers have evaluated its performance in different application scenarios, such as CAP performance in a beacon mode is evaluated in different scenarios on all three frequency bands [12], [13]. The performance of CFP is also analyzed and evaluated in different scenarios. Besides, different models are proposed to improve the CFP efficiency. In [14], Multi-Factor Dynamic GTS Allocation Scheme (MFDGAS) is proposed in which, CFP slots allocation is improved by offering better link utilization and transmit more data traffic at the cost of fairness of data. However, QoS is compromised due to latency issues. Yang and Zeng [15] improves the link utilization of the CFP slots by dividing the entire CFP slots from 7 to 32. In [16], the PAN coordinator segregates the data requests by prioritizing the nodes with emergency data requests. Xia *et al.* [17] allocates CFP slots by introducing Adaptive and Real-Time GTS Allocation Scheme (ARTGAS). Authors claim that ARTGAS meets the challenges of such applications where high data traffic is required. The authors further claim that ARTGAS increases bandwidth utilization without compromising the IEEE 802.15.4 standard. Multiple solutions have also been proposed for efficient allocation of CFP slots with better data transmission and better link utilization [18], [19].

Many critical wireless applications, such as body area sensor networks, have critical and real-time data traffic that requires immediate data delivery. This delay constraint is addressed by different researchers [20], [21]. In [20], an Explicit GTS Sharing and Allocation (EGSA) scheme is proposed to meet such applications where tighter delay bound data traffic is required. However, in [21], QoS is improved by minimizing the network delay and allows more CFP requesting nodes to send their data in CFP. Most of these schemes address CFP problems for uniform data traffic.

This paper deals with the problem of GTS assignment to the sensor nodes to maximize the throughput particularly for scenarios where variable data traffic is generated by each sensor node. The key challenge is to allow more nodes to send their data within a superframe structure. This can be achieved by adapting the duty cycle of the standard in an efficient way to improve link utilization. However, the standard does not meet the adaptive data requirements of GTS requesting nodes due to the following limitations.

- IEEE 802.15.4 standard does not allow the PAN coordinator to adjust its duty cycle to meet the adaptive data traffic.
- The standard does not allow more than 7 nodes to send their data in a beacon interval.

In this work, an Optimal GTS Allocation Mechanism with Adaptive Duty cycle (*OGMAD*) is proposed. *OGMAD* alters the superframe structure by changing its active and sleep period duration in accordance with the data requirements of the nodes in a beacon interval. *OGMAD* offers better throughput with reduced network delay and accommodates more nodes to transmit their data within a super-frame duration.

Major contributions of *OGMAD* are:

- *OGMAD adapts the active and sleep period of the IEEE 802.15.4 standard according to traffic requirements. This improves the GTS utilization and data transmission in a super-frame duration.*
- *OGMAD allows more than 7 nodes to send their data within a single superframe structure. Whereas, the standard does not allow more than 7 nodes to transmit their data.*
- *OGMAD helps the PAN coordinator to scrutinize GTS requesting nodes efficiently by applying the knapsack optimization algorithm along with Longest Job First (LJF). It not only improves the GTS utilization but also allows more nodes in transmitting their data during the contention-free period.*
- *OGMAD is quite compatible with IEEE 802.15.4 standard with minute changes in existing parameter values of standard.*

Rest of the paper is organized as follows: A brief overview of the IEEE 802.15.4 standard is described in section II. In section III, the proposed schemes along with different algorithms are described. Section IV analyzes the performance of the proposed schemes with the IEEE 802.15.4 standard. Finally, Section V concludes the paper.

II. OVERVIEW OF IEEE 802.15.4 STANDARD

IEEE 802.15.4 standard is designed for low-rate and low power Wireless Personal Area Networks (LR-WPAN) and operates on physical and MAC layers [22], [23]. It operates in two modes such as beacon-enabled and non-beacon enabled

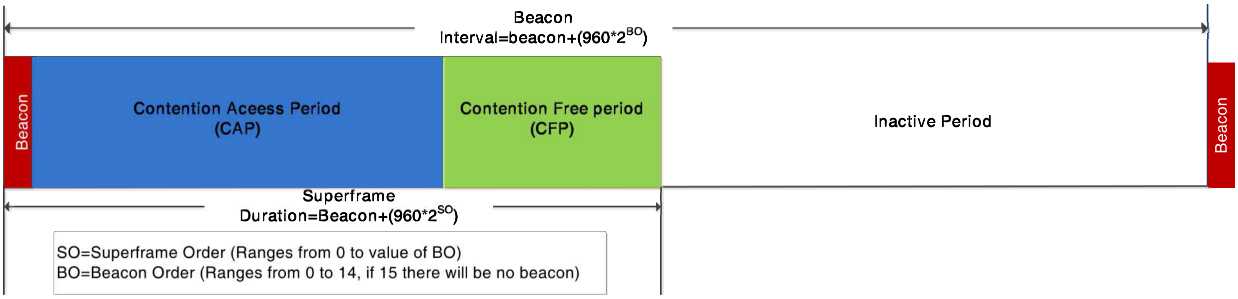

FIGURE 1. Superframe structure of IEEE 802.15.4 standard.

modes and deployed in the star as well as in peer-to-peer fashion [24], [25].

During non-beacon enabled mode, nodes are connected in an ad-hoc manner and follow the un-slotted CSMA/CA algorithm in communicating its data with its peer node. However, in a beacon-enabled mode, there is a coordinator node called PAN coordinator and rest are member nodes in a WPAN. Nodes communicate with the coordinator to transmit their information. PAN coordinator is responsible to broadcast a beacon frame and all the member nodes are required to listen to this beacon for time synchronization. A superframe structure is introduced in a beacon-enabled mode, that comprises an active period also known as Superframe Duration (SD) and an optional inactive period. *SD* starts with a beacon frame and followed by a CAP and CFP. PAN coordinator informs nodes about the start of CAP, the start of CFP, slot duration and the arrival of the next beacon message. The interval between two consecutive beacons is called Beacon Interval (BI). SD comprises of 16 equal duration slots. CAP along with beacon frame comprises of minimum 9 slots whereas CFP contains a maximum of 7 slots of the SD. In CAP, nodes communicate by following the slotted CSMA/CA algorithm. However, in CFP, nodes are assigned Guaranteed Time Slots (GTS) for transferring their data to the PAN coordinator. Nodes prefer to transfer their data to the PAN coordinator during CFP with guaranteed transmission. A complete superframe structure is shown in Fig. 1. A list of important symbols used throughout this paper and their meanings are listed in Table 1.

SD and BI solely depend on the fixed-parameter value of *aBasesuperframeduration* and variation in their lengths is controlled by parameter values of Superframe Order (SO) and Beacon Order (BO) respectively, as mentioned in equations 1 and 2.

$$SD = aBasesuper\ frameduration \times 2^{SO} \quad (1)$$

$$BI = aBasesuper\ frameduration \times 2^{BO} \quad (2)$$

where, $0 \leq SO \leq BO < 15$.

Duty cycle (DC) is defined as the active period in a total duration. Active period and total duration in IEEE 802.15.4 standard rely on parameter values of *SO* and *BO*, So *DC* in the standard is calculated as:

$$DC = 2^{BO-SO} \quad (3)$$

TABLE 1. List of important symbols and their meanings.

Symbol	Meaning
SD	Superframe Duration
BI	Beacon Interval
GTS_{req}	Number of GTS required by a node
DR	Data requests by a node
SC	Slot capacity in bits
R_{Nodes}	Total GTS requesting nodes
R_{slots}	Accumulated GTS requested by R_{Nodes}
RS_{new}	GTS allocated by PAN in new superframe
RN_{succ}	Total successful nodes
N_{LJF}	Scrutinized nodes after applying Longest Job First
R_{LJF}	Total slots required by N_{LJF} nodes
GTS_{Max}	Maximum GTS available in next superframe after adjusting SO
N_{NLJF}	Left over nodes after excluding N_{LJF}
R_{NLJF}	Left over slots after allocating R_{LJF}
GTS_{dur}	GTS duration

A. GTS ALLOCATION PROCEDURE

In IEEE 802.15.4 standard, the PAN coordinator allocates GTS to only those nodes which are associated members of its WPAN and are assigned a short address. The number of GTS required by a node (GTS_{req}) to send its data request (DR) can be calculated by knowing the slot capacity (SC) in an SD as mentioned in eq.4.

$$GTS_{req} = \lceil DR/SC \rceil \quad (4)$$

Here, SC is computed as:

$$SC = 960 \times 2^{SO-2}(bits) \quad (5)$$

A GTS requesting node, after computing its GTS_{req}, sends a request to the PAN coordinator during CAP. A GTS request frame format is shown in Fig.2.

PAN coordinator after broadcasting beacon frame, remains in receiving mode throughout the CAP to receive nodes requests. After receiving all GTS requests, the PAN coordinator evaluates them. If accumulated GTS requested by nodes is less than 8, then all the requesting nodes are allocated GTS according to their requests. If the number of GTS requested by nodes is more than 7, then the PAN coordinator scrutinizes GTS to adjust them within the available slots on First Come First Serve (FCFS) basis. PAN coordinator informs all

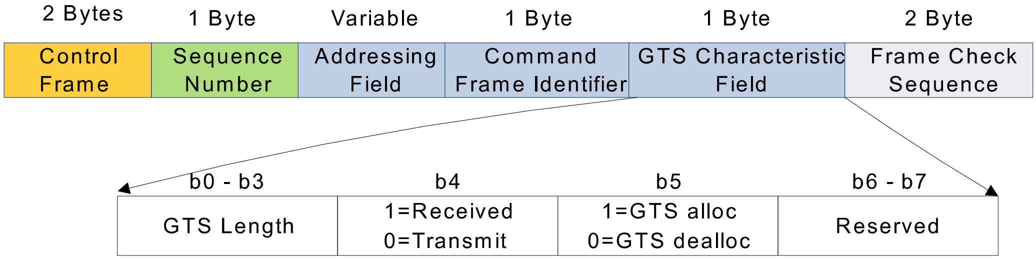

FIGURE 2. GTS request frame format of IEEE 802.15.4.

successful nodes about their starting slot number with the number of slots allocated during the next beacon frame. The successful nodes retrieve their allocated CFP slots from the GTS list shown in the GTS field of the beacon frame as shown in Fig.3.

A GTS field comprises the following parts.

- *GTS Specification:* It comprises of 8 bits, $b_0 - b_2$ inform about the number of nodes that are allocated GTS in the coming BI and last bit b_6 permits these nodes. However, bits $b_3 - b_6$ are reserved for future use in the standard.
- *GTS Direction:* It comprises 8 bits and its seven bits $(b_0 - b_6)$ describe the transmission or reception of data to a maximum of 7 GTS allocated nodes.
- *GTS List:* This portion of the GTS field describes the short address of all GTS allocated nodes with their starting slot number and their allocated GTS slots. The length of the GTS list increases with the increase in the number of GTS allocated nodes.

The standard does not allow the PAN coordinator to adjust its SD and BI in accordance with the data traffic requirements in a superframe. When requesting data is more than the available limit within an active period, then some of the nodes will not be entertained. However, if requesting data is far less than the available limit then slot size need to be reduced accordingly. In this work, the active period of the standard is adapted in accordance with the requested data and nodes are allocated GTS based on a new calculated superframe duration.

III. PROPOSED OGMAD SCHEME

This section describes our proposed scheme that offers Optimal GTS allocation Mechanism with Adaptive Duty cycle (*OGMAD*). In *OGMAD*, PAN coordinator adjusts the superframe duration in accordance with the total number of GTS requests (R_{slots}) received by all GTS requesting nodes (R_{Nodes}). In addition, *OGMAD* adapts the CFP slot duration along with number of CFP slots. This helps in increasing the GTS utilization and assign more R_{Nodes} as compared to the standard in transmitting their data. In this work, all the required steps in GTS allocation are described separately in a comprehensive manner, such as GTS requesting procedure in the proposed scheme, working of *OGMAD* algorithm, and slot selection procedure.

TABLE 2. Reserved bits in GTS characteristic filed.

b0 - b3 (GTS Req)	Value of X	b6, b7 (Reserved bit)	Description
0001	0	00	More than 50% slot is occupied
0001	1	01	GTS between 25% to 50% is occupied
0001	2	10	GTS between 12.5% to 25% is occupied
0001	3	11	GTS between 6.25% to 12.5% is occupied

A. GTS REQUEST FRAME STRUCTURE

Every member of (R_{Nodes}) is required to determine its (GTS_{req}) individually as described in eq. 5. Due to adaptive GTS_{req} in each superframe, CFP length needs to be increased or decreased to manage the GTS utilization optimally. *OGMAD* allows each member of R_{Nodes} to send GTS_{req} from a fractional value of SC slot to maximum of 15 slots with the help of bits $b0 - b3$ of GTS characteristic fields of Fig.2. The fractional value will be considered for all those nodes, whose $GTS_{req} = 1$, and it is calculated as:

$$GTS_{req} = \frac{DR}{SC} \tag{6}$$

This equation will generate the GTS_{req} in fraction number. Each member of R_{Nodes} will send this fractional value to the PAN coordinator by using two reserved bits b6 and b7 in the GTS characteristic field of GTS request frame format as shown in Fig. 2. The values of b6 and b7 are determined by calculating the value of X as:

$$X = \left|\left\lceil log_2(\frac{DR}{SC}) \right\rceil\right| \tag{7}$$

These two bits are computed as shown in Table 2:

These additional bits inform the PAN coordinator to analyze the GTS requests in a precise manner. When $b0$ to $b3$ is 0001, it means node requires only one GTS. In this case, $b6$ and $b7$ help PAN coordinator to compute the slot the portion in percentage. If R_{slots} are less than the maximum available limits, then the PAN coordinator needs to reduce the value of next SO accordingly. According to the standard, a decrease in SO by 1 reduces the GTS capacity to half of

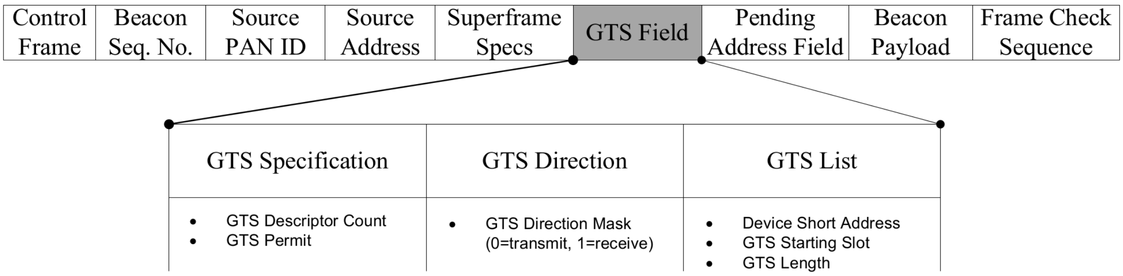

FIGURE 3. Beacon frame with GTS field in IEEE 802.15.4.

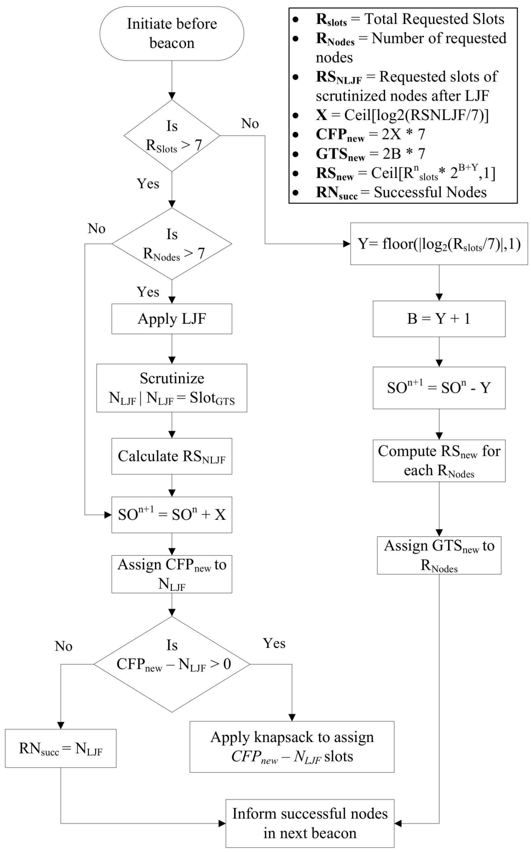

FIGURE 4. Proposed algorithm for adaptive duty cycle in IEEE 802.15.4 standard.

the initial capacity. This is why the PAN coordinator needs to determine the precise value of R_{slots}. On the other side, bits b0 to b3 of the GTS characteristic field allow each node to send a maximum of 15 slots request to the PAN coordinator. PAN coordinator after receiving all these GTS requests apply the *OGMAD* algorithm as described in III-B

B. OGMAD ALGORITHM

PAN coordinator after receiving all the requests from R_{Nodes} applies the *OGMAD* algorithm. The algorithm not only adjusts the SO and BO values optimally but also assign GTS to more than 7 nodes. Flow chart of *OGMAD* is shown in Fig.4.

PAN coordinator applies this algorithm and adapts new SO (SO^{n+1}) in two different scenarios.

1) when $(R_{slots}) \leq 7$.
2) When $(R_{slots}) > 7$.

1) REQUESTING SLOTS LESS THAN AVAILABLE LIMIT

When R_{slots} are less than the available limits, that is 7, then value of SO^{n+1} may be reduced by applying the following equation.

$$SO^{n+1} = SO^n - Y \tag{8}$$

here, Y is calculated as:

$$Y = \left\lfloor \left| (log_2(\frac{R_{slots}}{7}) \right|, 1) \right\rfloor \tag{9}$$

Maximum number of CFP slots available in next superframe duration GTS_{Max} are calculated as $2^{Y+1} \times 7$. Number of GTS required by each member of R_{Nodes} (RS_{new}) is recomputed as:

$$RS_{new} = \left\lceil GTS_{req} \times 2^B, 1 \right\rceil$$

PAN coordinator assigns GTS_{Max} to R_{Nodes} and informs successful nodes (RN_{succ}) in the beacon frame along with their allocated starting slot and value of SO.

During the next superframe, all GTS requesting nodes will compute their GTS_{req} based on new SO, that is, SO^{n+1}.

2) REQUESTING SLOTS GREATER THAN AVAILABLE LIMIT

If R_{slots} and R_{Nodes} are more than the maximum available GTS limit of 7, the PAN coordinator will apply Longest Job First algorithm (LJF) on all R_{Nodes} and scrutinize first 7 nodes (N_{LJF}) which have their highest GTS requests. The number of slots of these N_{LJF} (R_{LJF}) will help PAN coordinator in determining the new SO value (SO^{n+1}) with the help of the following equation.

$$SO^{n+1} = SO^n + X \tag{10}$$

$$Here,\ X = \left\lceil log_2(\frac{R_{LJF}}{7}), 1 \right\rceil$$

The increased value of SO^{n+1} increases the active duration with the increase in CFP duration. For example, if the value of SO^{n+1} is incremented by 1, then the active period will be doubled and consequently, the number of GTS will also be

TABLE 3. Optimal CFP utilization to Knapsack mapping.

	Maximum CFP Utilization Problem	Knapsack Problem
R_{NLJF}	Maximum number of available slots	Carrying capacity of the Knapsack
N_{NLJF}	CFP requesting nodes	Items to be packed
GTS^b_{req}	Data slot(s) request by a node	Weight/Value of an item

doubled. However, each CFP slot keeps its previous duration. PAN coordinator allocates GTS to all (N_{LJF}). If there is any GTS left, then it will be allocated to other nodes by applying the knapsack optimization algorithm as described in section III-B.3.

3) KNAPSACK OPTIMIZATION

Knapsack algorithm allows to fill a limited space with the maximum valuable items and picks *most valuable items* of different *weights* and *values* within its *carrying capacity*. In *OGMAD*, we need to optimally allocate the remaining CFP slots (after successful allocation of N_{LJF} nodes) to the leftover nodes. It is formulated in the Knapsack problem, that is, PAN coordinator has to accommodate $N_{NLJF} = R_{Nodes} - N_{LJF}$ nodes within the capacity of $R_{NLJF} = (2^X \times 7) - R_{LJF}$ slots. The goal is to accommodate maximum of these slots by allowing maximum nodes to transmit. In this problem, weights and values of requesting nodes are the same value i.e., equal to their requesting slots. This problem of maximum slots utilization by allowing the maximum number of nodes to send their data can be mapped to the 0-1 Knapsack problem in the following way:

- M = Maximum carrying capacity of knapsack that is equal to total available GTS $((2^X \times 7) - R_{LJF})$ in CFP.
- GTS^b_{req} = Number of slots requested by node b and it is considered as its weight and value.
- m: current slot number $(0 \leq m \leq ((2^X \times S_{GTS}) - R_{NLJF}))$.

The knapsack problem is solved in two steps.

1) by filling a knapsack table
2) selecting optimum nodes from the table

If PAN coordinator receives R_{NLJF} slot(s) requests from $R_{Nodes} - N_{LJF}$ nodes, then it checks whether $R_{NLJF} > (2^X \times 7) - R_{LJF}$ or not. In case, R_{NLJF} is less than the available slots then all the requesting nodes are assigned data slots according to their requests by applying the shortest job first algorithm. Otherwise, the PAN coordinator scrutinizes the nodes by filling the knapsack table by following the algorithm shown in Fig.5. This algorithm fills a knapsack *OGMAD* table that comprises of $R_{Nodes} - N_{LJF} + 1$ rows and $(2^X \times 7) - R_{NLJF} + 1$ columns.

Once all the cells of the table, i.e., $X[0, 0]$ to $X[R_{Nodes} - N_{LJF}, (2^X \times 7) - R_{NLJF} + 1]$ are filled, then optimized nodes are selected from this table by following the algorithm shown in Fig.6. The node selection criteria starts from the bottom right cell and compare it with its upper cell value. Once the value of this cell is greater than its upper value then the node

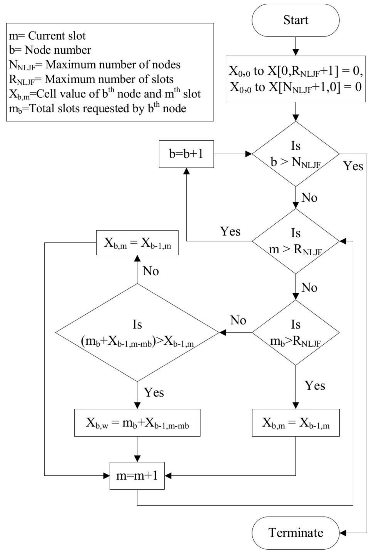

FIGURE 5. Knapsack OGMAD table implementation.

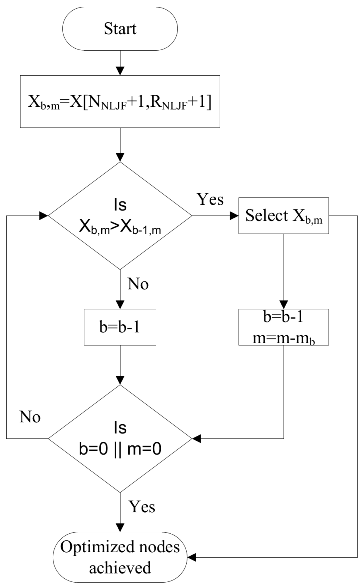

FIGURE 6. Optimum nodes selection algorithm from Knapssack table.

will be selected, otherwise, it will move to its upper row in the same column.

RN_{succ} in this scenario is the sum of scrutinized nodes after the knapsack algorithm and N_{LJF}. In this way, *OGMAD* tune *SO* according to the traffic requirements to accommodate more nodes as well as offer better GTS utilization in a *BI*. It allows the PAN coordinator to adjust the next superframe duration according to the GTS requests received by R_{Nodes} to accommodate them efficiently. The performance of *OGMAD* in accordance with its *SO* adjustment is shown in Fig. 7. In this figure, the performance of *OGMAD* in accordance with its *SO* adjustment is monitored for three different data sets. This is the case when all R_{Nodes} requires GTS to send a different amount of data to the PAN coordinator. It is evident

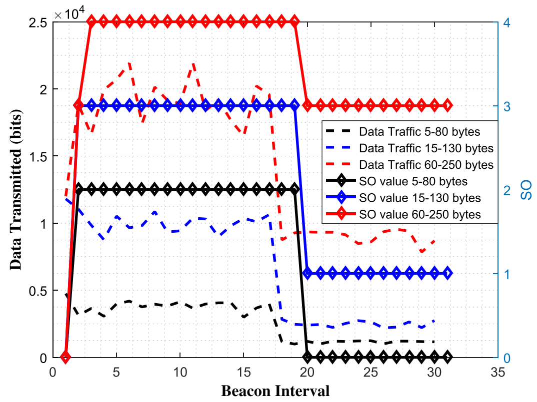

FIGURE 7. Superframe duration adjustment of OGMAD against varying data requests.

from the results, that *OGMAD* helps PAN coordinator to adjust its *SO* to accommodate traffic requirements optimally.

C. DETERMINATION OF ALLOCATED GTS BY A NODE

PAN coordinator informs GTS requesting nodes about their successful allocation in the next beacon frame. In beacon, each successful GTS requesting node is informed about its starting slot and number of slots allocated to it in the GTS list of GTS field as shown in Fig. 3. GTS requesting nodes only need to know about the CFP slot duration (GTS_{dur}), that can be determined as:

$$GTS_{dur} = 60 \times 2^{min[SO^n, SO^{n+1}]}(Symbols) \tag{11}$$

Nodes in the PAN need to know about the CAP length (CAP_{dur}) and it can easily be determined by each node by subtracting the CFP with the help of eq. 12

$$CAP_{dur} = 960 \times 2^{max[SO^n, SO^{n+1}]} - (RN_{succ} \times GTS_{dur}) \tag{12}$$

here, RN_{succ} is the accumulated GTS allocated to all nodes in the superframe duration. A node can find out the RN_{succ} from the GTS descriptor count available in GTS specification of GTS field as shown in Fig. 3.

IV. NUMERICAL ANALYSIS AND RESULTS

This section analyzes the performance of *OGMAD* with the IEEE 802.15.4 standard. The comparative analysis comprises of the amount of data transmitted, network delay, GTS Utilization, and number of nodes assigned GTS during CFP.

A. SIMULATION ENVIRONMENT

To validate the comparative performance of *OGMAD* with the IEEE 802.15.4 standard, a simulation environment comprising of 21 sensor nodes (1 PAN coordinator and 20 member nodes) is developed in MATLAB. All these nodes are randomly deployed in an area of 100 × 100 square meters. Each member node is assigned some data that is required to be transmitted to the PAN coordinator during CFP. The performance of *OGMAD* is evaluated by comparing it with the IEEE 802.15.4 for three different random data sets as well as for the fixed amount of adaptive data assigned to each node with varying parameter values of SO and BO. The main parameters and their values used in this simulation are shown in Table 4.

TABLE 4. Simulation parameters.

Parameters	Values
Number of Nodes	21
Network Size	$100m \times 100m$
Data Rate	$250Kbps$
Random Data Set 1 (Bytes)	10-40
Random Data Set 2 (Bytes)	40-70
Random Data Set 3 (Bytes)	90-120
Fixed Offered Load (Bytes)	15:5:200
Initial Superframe Order in OGMAD	0
Initial Beacon Order in OGMAD	0
GTS Duration in 802.15.4 (sec)	$9.6 \times 10^{-4} \times 2^{SO}$
GTS Duration in OGMAD (sec)	$4.8 \times 10^{-4} \times 2^{SO}$

B. DELAY CALCULATION

Delay of a node in transmitting its data is the total time calculated when a node has data request from its upper layer till the successful transmission of data to its PAN coordinator. If a node n has data request of D amount of data just before the commencement of beacon frame, then its delay in transmitting this data in *OGMAD* (D_{OGMAD}) is calculated as:

$$D^n_{OGMAD} = BI + SD - (\sum_{b=1}^{b=n} K_{b-1} \times t_{OGMAD}) \tag{13}$$

Here,

$$t_{OGMAD} = min[9.6 \times 10^{-4} \times 2^{SO^n}, \quad 9.6 \times 10^{-4} \times 2^{SO^{n+1}-1}](sec)$$

and K_{b-1} is number of slots allocated to node n and its preceding nodes.

If Y nodes are assigned GTS successfully, then total delay of the network in OGMAD (D^{max}_{OGMAD}) is calculated as:

$$D^{max}_{OGMAD} = \sum_{i=1}^{i=Y}[BI_i + (\sum_{b=1}^{b=i} K_b \times t_{OGMAD})] \tag{14}$$

However, delay of a node n in IEEE 802.15.4 standard (D_{stnd}) in transmitting same amount of data is calculated as:

$$D_{stnd} = BI + SD - (\sum_{b=1}^{b=n} K_{b-1} \times t_{stnd}) \tag{15}$$

Here,

$$t_{stnd} = 9.6 \times 10^{-4} \times 2^{SO}(sec)$$

If PAN coordinator successfully assigns CFP slots to K nodes, then accumulated delay in the network by IEEE 802.15.4 standard (D^{max}_{stnd}) is calculated as:

$$D^{max}_{stnd} = \sum_{i=1}^{i=X}[(BI + SD)_i - \sum_{x=1}^{x=i} K_{x-1} \times t_{stnd}] \tag{16}$$

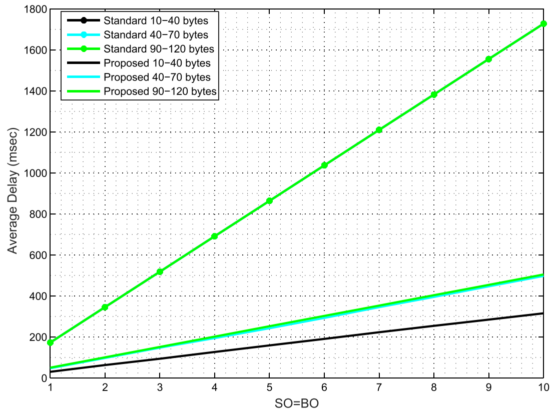

FIGURE 8. Accumulated average delay comparison for random data sets.

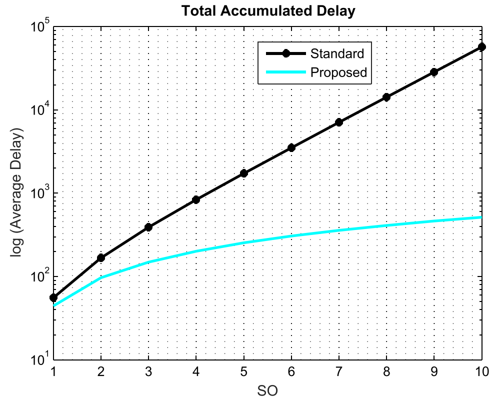

FIGURE 9. Accumulated average delay comparison for fixed data of successful nodes.

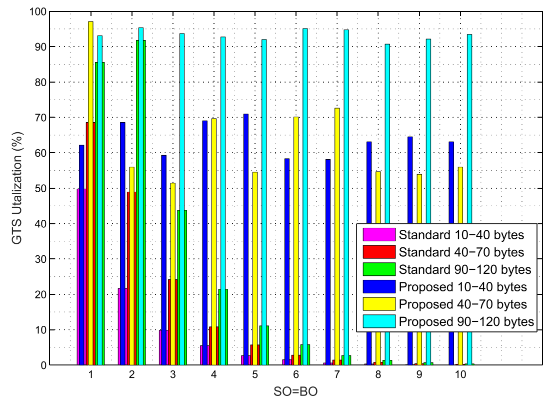

FIGURE 10. GTS utilization comparison for random data sets.

Fig. 8 shows delay comparison between *OGMAD* and the IEEE 802.15.4 standard. The results are obtained for three different random data sets as shown in Table 4. The average delay of all the nodes that successfully transmitted data using *OGMAD* is evaluated for different ranges of SO and BO with a 100% duty cycle. The previous average delay is accumulated in the average delay calculated in the next BI. The standard offers same amount of delay for all the three different data sets due to same SO and BO (hence the result for three different data sets using standard algorithm is the same line in the graph), whereas, *OGMAD* adjusts its *SO* and *BO* in accordance with the data traffic and it is more for higher amount of data traffic and less when nodes have lower amount of data traffic. The results show that for all the three random data sets, the standard offers significantly large delay as compared to *OGMAD*.

The results shown in Fig. 9 are obtained when each GTS requesting node needs to transmit a fixed amount of data in all beacon intervals. However, this assigned data to each node varies from all the other nodes. For better clarity and comparison, the results are shown on a logarithmic scale. The average delay of all nodes in a beacon interval is accumulated with the average delay of previous beacon intervals. It is evident from the results that in the standard, there is a huge amount of delay for different values of SO. In comparison, *OGMAD* has little and consistent delay, because it adjusts the SO accordingly.

C. LINK UTILIZATION

Link utilization of CFP is calculated as the ratio of the CFP slots used for data transmission to the total available slots in a beacon interval. The standard does not adapt to the GTS duration, hence a significant amount of bandwidth is wasted when nodes have adaptive data traffic. *OGMAD* allows the PAN coordinator to adjust its superframe duration in accordance with the data requests received by the sensor nodes. Moreover, it also allows the maximum amount of data requesting nodes in transmitting their data by equally segregating the GTS. Also, *OGMAD* applies the knapsack algorithm to further optimize the unused CFP slots by allowing more nodes to send their data traffic. This optimization improves GTS utilization by allowing more data traffic in a specific time frame. In addition, *OGMAD* allows maximum nodes in transmitting their data in a contention-free manner.

Fig. 10 shows GTS utilization comparison between *OGMAD* and the standard. The results show that the GTS utilization in the standard decreases with the increase in SO value for all data sets. This is due to the increased ratio of unused GTS in each CFP slot. However, *OGMAD* adjusts its GTS duration in the light of the incoming data requests. This is why it shows a similar GTS utilization trend in all beacon intervals.

Results shown in Fig. 11 further verifies that when the nodes have adaptive data traffic and this data is fixed in all beacon intervals, *OGMAD* offers better GTS utilization as compared to the standard. It is evident from the results that the GTS utilization of *OGMAD* is significantly larger than the standard for all the different values of SO specified in the standard.

D. DATA TRANSMISSION

Data transmission during CFP is calculated as the amount of data transmitted by GTS requesting nodes in a super-frame

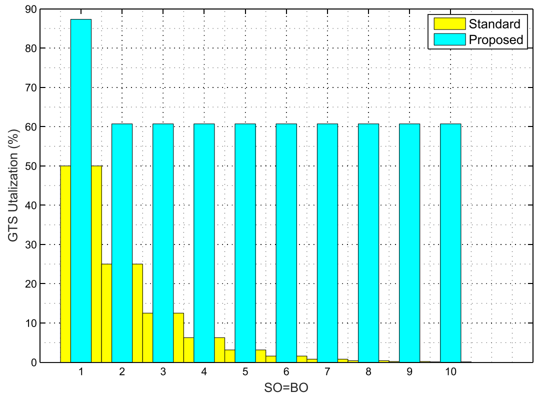

FIGURE 11. GTS utilization comparison for fixed data of successful nodes.

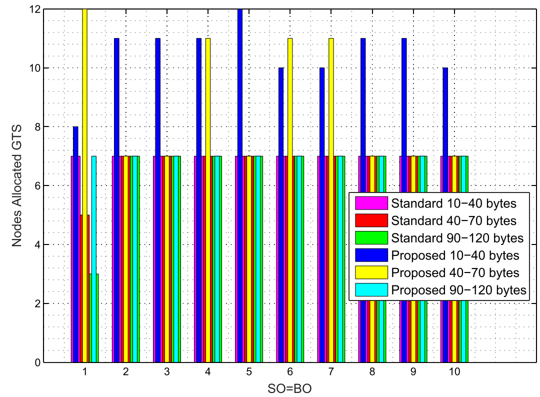

FIGURE 14. Nodes allocated GTS for varying data offered by each node.

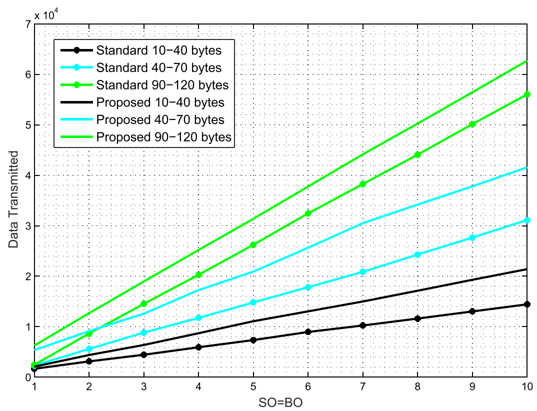

FIGURE 12. Data transmitted in each beacon interval for varying data traffic.

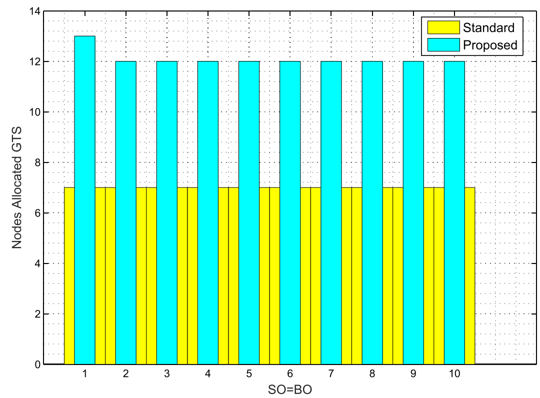

FIGURE 15. Nodes allocated GTS in each beacon interval for varying data traffic.

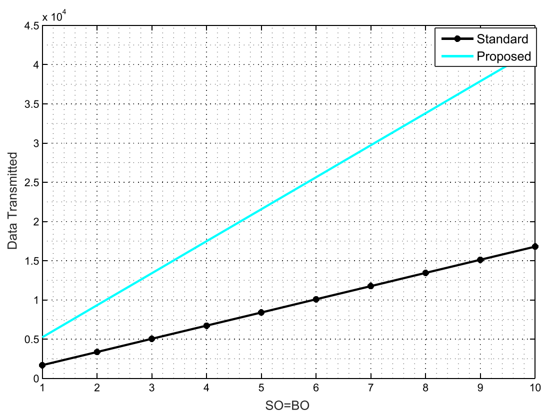

FIGURE 13. Network data traffic against varying load for each node.

duration. Results shown in Fig. 12 and Fig. 13 compares the amount of data transmitted during CFP by *OGMAD* and the standard.

The results shown in Fig. 12 verifies that the data transmission in *OGMAD* is better than the standard for all three random data sets. The same trend is shown in Fig. 13 when nodes are allocated a fixed amount of data in each beacon interval, however, the data of each node is different from the other nodes. It is evident from the results that the data transmission in *OGMAD* is much better than the standard for a different types of data sets. This is because *OGMAD* allows more nodes in transmitting their data during CFP.

E. GTS ALLOCATED NODES

IEEE 802.15.4 standard only allows a maximum of 7 nodes to transmit their data during CFP in a super-frame duration. This is one of the major limitations of the standard. When the number of GTS requests increase from the available limit, then it scrutinizes GTS requesting nodes on a first come first serve basis. However, *OGMAD* adjusts superframe duration according to the requests and can increase the CFP slots to accommodate more nodes efficiently.

In Fig.14, we can see that *OGMAD* accommodates more GTS requesting nodes in transmitting their data as compared to the standard for all random data sets and for all values of SO in a beacon interval. Fig. 15 plots the number of nodes that are allocated GTS when a fixed amount of data is allocated to the nodes in each beacon interval (however, the data of each node is different from the other nodes). It is evident from the results that *OGMAD* allows $5-6$ more nodes in transmitting their data as compared to the standard.

V. CONCLUSION AND FUTURE WORK

In this work, an Optimal GTS allocation Mechanism for Adaptive Duty cycle called *OGMAD* is proposed. *OGMAD* adjusts the active period of the superframe in accordance with the requested data by adjusting the value of SO. To implement optimal GTS allocation, *OGMAD* adds few reserved bits in the message format of the IEEE 802.15.4 standard. In *OGMAD*, CFP allocation is done to improve link utilization by accommodating more GTS requesting nodes. Analytical results verify that the *OGMAD* reduces network delay, improves link utilization, offers better data transmission, and allows more GTS requesting nodes to transmit their data as compared to the conventional IEEE 802.15.4 standard. In the future, we aim to optimize the GTS allocation for energy harvesting-based IoT devices. Particularly, in scenarios where IoT nodes need to harvest energy during their sleep period, the GTS allocation mechanism has to be carefully designed to consider factors such as battery lifetime, network traffic load, and QoS requirements.

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