An efficient medium access control protocol for RF Energy Harvesting based IoT devices

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Abstract

Energy efficiency is one of the major challenges in IEEE 802.15.4 based Internet of Things (IoT). In the Medium Access Control (MAC) layer of the IEEE 802.15.4 standard, Guaranteed Time Slot (GTS) are allocated to the IoT devices for data transmission. However, GTS allocation does not consider residual energy of IoT devices resulting in reduced life cycle of these devices. In this paper, we propose an efficient MAC protocol for RF harvesting based IoT devices. The proposed protocol uses residual energy based duty cycle adaptation to prioritize transmission of high energy devices, allowing low energy devices to harvest energy in the mean time. Simulation results show that the life cycle and transmitted data of IoT devices is improved up to 94% and 79% respectively by using the proposed protocol, as compared to the IEEE 802.15.4 standard.

Keywords: Internet of Things, Wireless Sensor Networks, Energy Harvesting, IEEE 802.15.4, GTS

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1. Introduction

The idea of robust and effective global computing infrastructure has been presented for many years. Wireless communication technology plays a vital role to enable such a widely interconnected computing environment [1, 2]. The blending of sensing and wireless interaction has paved the path to the growth of the Internet of Things (IoT). One of the key components of the IoT network is wireless sensor nodes. These sensor nodes are battery operated with limited energy and low processing capabilities. These IoT based wireless sensor nodes send their information to their gateway either in single or in multi-hop fashion over unreliable links.

IoT technology has enabled a plethora of potential applications ranging from environment monitoring [3], tactical military application, Body Area Networks (BAN) [4, 5], home automation [6], vehicular ad hoc networks [7, 8, 9], smart cities [10, 11], and object tracking. As a result, it is expected that shortly, many IoT applications will be commercialized and available for public use.

Energy efficiency is a key challenge in IoT devices [12, 13]. Since the sensor devices are powered by the battery and once the energy of a node is exhausted, it will no more able to contribute to the network until the battery is changed or recharged. Replacing the exhausted batteries of sensors mass deployed in the outdoor situation is a difficult task and it also increases the operational expenditure. It is hence essential to conserve the battery power by improving the energy efficiency of the IoT sensor devices, resulting in increased lifetime [14, 15, 16]. Different Medium Access Control (MAC) protocols have been proposed for IoT based WSN by emphasizing on their energy limitations. IEEE 802.15.4 standard was developed for such Wireless Personal Area Networks (WPAN) which are low power and require a low data rate with low processing. This is the reason, they are suited for WSNs and IoT applications [17].

It has been observed that some of the nodes in a network have to send and receive more data as compared to other nodes in that network. The node with an increased amount of transmitting and receiving data consumes its energy quickly as compared to the nodes with less amount of data transmitting or receiving. This causes an imbalance in the residual energies of nodes in a WPAN resulting in network instability. To increase the life cycle of all nodes, load balancing is required by allowing nodes to transmit or receive more data that have more remaining energy as compared to other nodes.

Recently, Energy Harvesting (EH) has been a vital research area to enhance the energy efficiency of IoT devices. EH refers to the mechanism of obtaining energy from the ambient surrounding like solar energy, kinetic energy (wind and mechanical vibration), and wireless energy (radio frequency). The energy from these sources can be transformed into electrical energy and can be directly consumed to operate the sensor node or first deposited in a storage battery and then supplied to the sensor nodes. Deployment of EH methods enables the sensor nodes to charge their on-board batteries in the working environment resulting in low operation cost and avoidance of network downtime. Consequently, energy harvesting based IoT devices has been gaining substantial attention.

It is to be noted that all energy harvesting techniques can not offer limitless energy for an unlimited period, at any particular time only a finite quantity of energy can be obtained [18]. The energy level of sensor nodes increases when its energy consumption is less than its harvested energy. Generally, nodes increase their residual energy level when they are in sleep mode. However, their energy level decreases when they are transmitting or receiving any data as it consumes more energy during transmitting and receiving mode in comparison to harvested energy.

Energy-aware deep sleep mechanisms prefer the nodes with less residual energy to remain in sleep mode for energy conservation. In addition, it allows nodes to harvest energy during sleep mode. Nodes with low remaining battery power are better served if they are provided enough time to harvest energy and then proceed with their data transmission. This will save such nodes from battery depletion. The default IEEE 802.15.4 standard allows nodes to remain in sleep mode for a longer time even more than 99%, that allows node to harvest more energy during sleep mode. Increase in sleep time decreases throughput with increased network delay and Quality of service (QoS) is compromised.

To meet these challenges, we propose an Efficient MAC protocol for IoT based sensor networks ($E - MAC_{IoT}$), that helps PAN coordinator to adapt its duty cycle by considering the accumulated PAN energy without compromising the QoS. The proposed work based on RF based energy harvesting method that has been described in detail in prospect of IEEE 802.15.4 standard. In addition, it helps PAN coordinator to optimally scrutinizes GTS requesting nodes by considering their residual energy along with their data requests to increase their life cycle.

The main contribution of ($E - MAC_{IoT}$) includes:

1. ($E - MAC_{IoT}$) proposes an algorithm that allows the PAN coordinator to adjust its duty cycle based on the residual energy of the WPAN.
2. ($E - MAC_{IoT}$) proposes another algorithm that helps the PAN coordinator to scrutinize GTS requesting nodes by considering their individual residual energy levels and their data requests.
3. ($E - MAC_{IoT}$) is fully compatible with the IEEE 802.15.4 standard without compromising its existing parameters.

To evaluate the performance of $E - MAC_{IoT}$, a MATLAB based simulation environment is created and compared its performance with IEEE 802.15.4 standard in terms of network throughput along with their life cycle. The results show that the $E - MAC_{IoT}$ provides balanced power consumption of the sensor nodes, increases data transmission up to 79% with 94% improved lifetime of the network as compared to the standard.

The organization of the paper is as:

Section 2 gives an overview of the IEEE 802.15.4 standard. Section 3 describes different MAC protocols for IoT both with and without energy harvesting techniques followed by the proposed work in 4. The performance of the proposed scheme with the standard is evaluated in section 5, and section 6 concludes this paper.

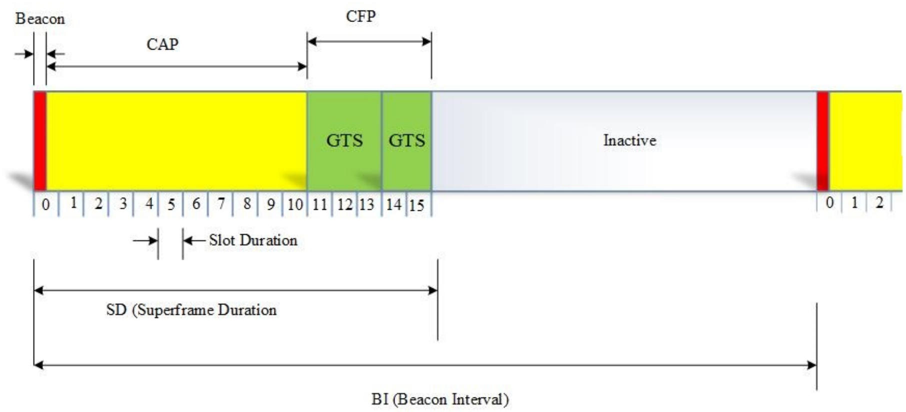

Figure 1: Superframe structure of IEEE 802.15.4 standard [19]

2. An overview of IEEE 802.15.4 Standard

The IEEE 802.15.4 standard is designed for Physical and MAC layers and operates in beacon and non-beacon enabled modes. During non-beacon enabled mode, nodes exchange their information in an ad-hoc manner. However, the beacon-enabled mode offers a superframe structure that comprises of an active and an inactive period. The active period starts with a beacon frame and followed by a Contention Access Period (CAP) and an optional Contention Free Period (CFP). PAN coordinator broadcasts the beacon frame by informing about CAP, CFP, and inactive period duration. During CAP, nodes send their all kind of requests by following the CSMA/CA method. During CFP, only selected nodes are allowed to explicitly send their data by allocating one or more Guaranteed Time Slots (GTS). The active period comprises of 16 equal duration slots, in which a maximum of 7 GTSs can be reserved during CFP. A complete superframe structure of IEEE 802.15.4 standard is shown in Fig. 1.

Beacon enabled mode allows the necessities of energy utilization and QoS because it supports a flexible low duty cycle (DC). The duration from the start of one beacon to the start of the next beacon is known as Beacon Interval (BI) and the active period is known as Superframe Duration (SD). During the inactive period, all nodes keep their radios off to conserve energy. BI and SD are calculated from the following equations as:

$$BI = 960 \times 2^{BO} symbols \quad (1)$$

$$SD = 960 \times 2^{SO} symbols \quad (2)$$

Each symbol duration of the standard in 2.4GHz frequency band is 16 μSec. The duty cycle is given as:

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

where $0 \leq SO \leq BO \leq 14$ [19].

Nodes preferred to send their data during CFP in their allocated GTS, as there is no collision. The standard allows the PAN coordinator to allocate GTS to only member nodes. A GTS requesting node first find out the number of GTS required (GTS_{req}) in transmitting its data L, that can be calculated as with the help of the following equation:

$$GTS_{req} = \lceil L/GTS_t \rceil \quad (4)$$

here, GTS_t represents the slot capacity. All nodes send their GTS_{req} to the PAN coordinator during CAP. PAN coordinator after receiving all these requests allocates GTS on First Come First Serve (FCFS) basis and informs all successful nodes about their starting slot in the next beacon frame. The successful nodes are allowed to send their data in their assigned GTS without interference of other nodes.

3. Related Work

Limited energy in wireless sensor nodes is one of their major constraints. Nodes need to conserve their energy to increase their life cycle. Energy harvesting is used to increase the energy level of the nodes. Many researchers proposed different MAC protocols to improve the energy efficiency of IoT based WSNs. In [20] RF-based energy harvesting algorithm (RF-MAC) is proposed. The algorithm proposes a procedure for energy harvesting in which energy harvesting occurs with the Request for Energy (RFE) packet. A sensor having low energy broadcast an RFE packet when the energy transmitter receives the RFE packet it sends the Cleared for Energy (CFE) packets. After receiving the CFE packet the sensor device broadcasts the ACK packet and therefore the energy transmitter emits energy.

In [21] an RF Adaptive Active Sleeping Period (RF-AASP) algorithm is proposed that adaptively varies the sleeping period of a sensor. The sleeping period is changed by adjusting the BO and SO value in reply to three things; variable bursty traffic load, arriving RF from energy transmitter, and the residual energy on the sensor device. In [22] an energy harvesting technique called SWIPT (simultaneous wireless information and power transfer) is proposed in which both the information and power are transferred simultaneously. In the proposed technique the energy efficiency in clustered based wireless sensor networks by fusing SWIFT with cooperative relays. The technique selects the optimal relay for forwarding the data by using the harvested energy and conserving its energy.

In [23] On-demand medium access control (ODMAC) protocol is proposed which is a receiver-initiated mac protocol for EH-WSN in which the receiver sends packets to the sender for informing them about the readiness of the receivers. In [24] REACH protocol for WSN is proposed in which the energy transmitter (ET) actively sends RF energy signals to the receivers with a request for energy (RFE) messages. The proposed method improves the energy harvesting rate, throughput, and lifetime of WSN. In [25], machine-to-machine (M2M) offloading communication mechanism is proposed for energy conservation in IoT environment. In [26], authors addressed fairness issues observed in industrial internet of things by applying first fairness-based transaction packing algorithm. In [27] probabilistic polling approached is used in which the sink varies the contention window to change the harvesting dynamic and the nodes having residual energy below a certain threshold will not take part in the contention process to conserve its energy thus improve the energy efficiency and lifetime of the network. In [28] AH-MAC is proposed and is based on Low-Energy Adaptive Clustering Hierarchy (LEACH). In AH-MAC only the end nodes such as cluster heads are responsible for energy harvesting while other nodes are not equipped with energy harvesting circuits and are only battery operated. Consequently, the lifetime of the network is improved by pursuing most of the activities by cluster heads.

In [29] IW-MAC is proposed in which the energy of the sensor nodes is mostly consumed by during actual data transmission while the control packets consume less energy thus more data packets and less control overhead packets are transmitted thus improves the energy of the IoT based sensor nodes. In [30], a scalable energy-efficient scheme for green IoT based heterogeneous wireless nodes is proposed that divides the area into different zones and uses the relay nodes for better use of transmission. The relay nodes are selected using the election process by considering parameters such as residual energy, distance, and centrality. In [31] a duty cycle adjustment algorithm for IoT enabled precision agriculture is proposed which improves the energy consumption and throughput of the network. The duty cycle is adjusted using the residual energy of the sensor nodes. In [32] a self-sustainable RF energy harvesting algorithm (SS-RF) for IoT based WSN is proposed in which RF energy is harvested from LTE eNodeB and the energy harvesting period is adapted in accordance to incoming traffic load and harvested energy using Kalman filters.

Although the above proposed methods improve the energy efficiency of the IoT based wireless sensor networks but there are some issues that need to be addressed. Table 1 shows the comparative table between different MAC protocols proposed in literature as [20], [21], [24],[30],[31],[32] does not guarantee distribution of traffic based on their energy levels thus no Load Balancing is applied also the concept of Energy-aware deep sleep in which the nodes with low residual energy will go to sleep and harvest energy is not applied in [20],[21],[23],[24],[27],[28],[30],[32]. Similarly, the concept of low energy devices to not take part in contention and the information about the next beacon transmission is missing in various proposed methods.

Table 1: Comparative table between different MAC

Protocol	Load Balancing	Energy-aware deep sleep	Contention Reduction	Wake-up time awareness
RF-MAC	NO	NO	YES	NO
RF-ASSP	NO	NO	YES	YES
ODMAC	YES	NO	YES	YES
REACH	NO	NO	YES	NO
AH-MAC	YES	NO	NO	NO
IW-MAC	YES	NO	YES	NO
SSES	NO	NO	YES	NO
H.Agrawal et al	NO	YES	YES	NO
SS-RF	NO	NO	YES	YES
$E-MAC_{IoT}$	YES	YES	YES	YES

IEEE 802.15.4 standard is highly attracted to IoT based WSNs due to its extremely low duty cycle. In this work, the proposed $E-MAC_{IoT}$ modifies this standard to improve the life cycle of the sensor nodes by offering load balancing by allowing nodes to remain in deep sleep when they are left with less energy.

4. Proposed Methodology

4.1. System Model

Inspired from [32], we consider a scenario as shown in Fig. 3 where a single-hop IoT network is in the proximity of LTE eNodeB. The IoT network consists of a central coordinator or sinks C and sensor nodes N = [1 2..... N]. The sensor nodes are assumed to have RF-harvesting capabilities. The sensor node consists of a low-power RF transceiver, low-power micro-controller, RF energy harvester, power management unit, and energy storage. The low-power RF transceiver is responsible for data transmission and reception in the IoT sensor node while the RF harvester is used to harvest energy from the LTE eNodeB. The reason for using two different antennas for data and energy is the different band of frequencies for LTE and IoT network.

In this paper, the Physical Broadcast Channel (PBCH) and Physical Down-link Control Channel (PDCCH) of the LTE are used for the energy harvesting

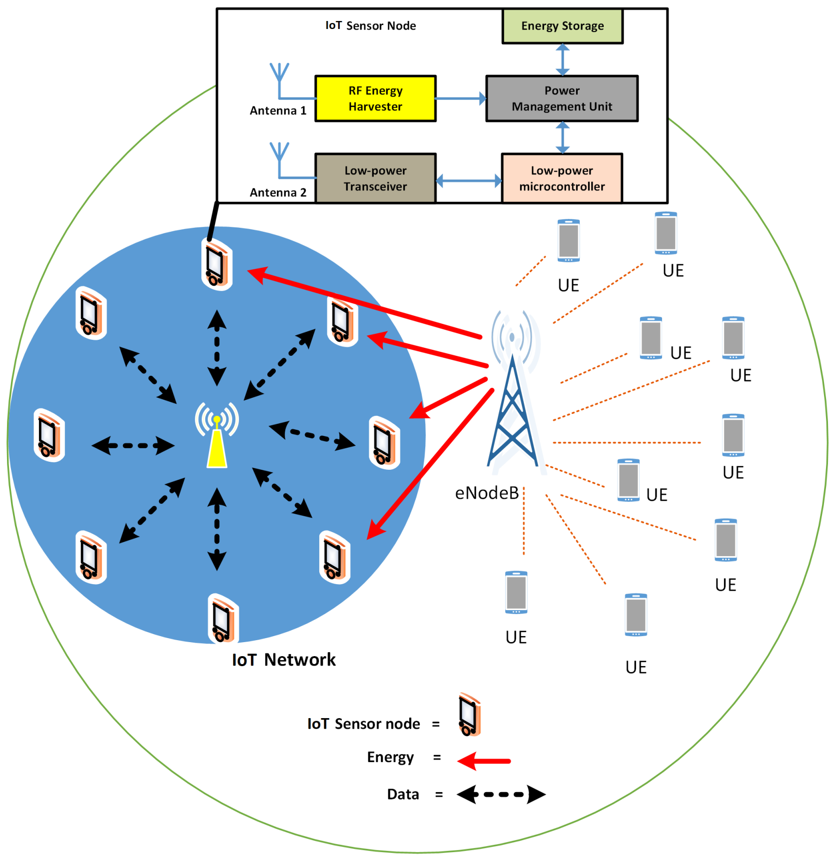

Figure 2: System Model

process. LTE transmission in the time domain occurs in a 10 ms frame sequence, which is divided into ten 1 ms sub-frames. The 1 ms sub-frame is further divided into two slots of 0.5 ms each. The PBCH is transmitted on the first four symbols of the first slot of the first sub-frame. The allocation of PBCH is spread over a duration of 40 ms (four radio frames) know as Transmission Time Interval (TTI). Duration of one OFDM symbol is $\tau_{sym} = 66.67$ μs when normal prefix is used, so the PBCH is on 4 OFDM symbols and is spread over 4 radio frames resulting in a total length τ_{PBCH} of 16 τ_{sym} in TTI.

The length of PDCCH depends on the number of OFDM symbols it has occupied. PDCCH is assigned to active UEs for controlling data transmission/reception. The actual number of OFDM symbols occupied by PDCCH depends on the number of active UEs requesting data transmission. Suppose γ_D represents the level of traffic load on the LTE network. As an example if the traffic load on the LTE network is divided into three levels, $\gamma_D = \{1, 2, 3\}$. In a dense LTE scenario, the traffic load is high, so the value of $\gamma_D = 3$. When the traffic load is average, $\gamma_D = 2$ and for low traffic loads, $\gamma_D = 1$. We assume that the traffic load in LTE remains the same for TTI = 40 ms, hence γ_D has a fixed value within a TTI. This yields the length of PDCCH $\tau_{PDCCH} = 40\gamma_D\tau_{sym}$ within a TTI [33].

4.2. RF Energy Harvesting

In our work, the primary concern is the harvested energy from the LTE eNodeB by the sensor nodes. Thus, we only consider the communication between the sensor nodes and the LTE eNodeB. In our model, the eNodeB is equipped with a single omnidirectional antenna and we also assume that the power control policy is not implemented on PBCH and PDCCH. Let P_i be the downlink transmit power of LTE eNodeB, d be the distance between the sensor nodes and the eNodeB, and a_{si} be the channel coefficient that contains both the effects of large-scale path loss and small-scale Rayleigh fading. Thus, the unit amount of energy harvested at the sensor nodes as given by [21] will be equal to:

$$eu = \zeta(\tau_{PDCCH} + \tau_{PBCH})\frac{P_i|a_{si}|^2}{d^\alpha} + \sigma^2 \tag{5}$$

where ζ is the efficiency of RF to DC and σ^2 denotes the noise power also the τ_{PBCH} and τ_{PDCCH} are the time duration of channels. As Rayleigh fading is assumed so the amplitude square of projection a_{si} is denoted by $|a_{si}|^2$.

Now as the sensor node goes to sleep mode and will stop its transmission but will continue to harvest energy from LTE eNodeB harvested energy during the beacon interval will be equal to:

$$E_h = \left(\frac{\tau_{active} + \tau_{inactive}}{\tau_{frame}}\right) \times eu \tag{6}$$

$$E_h = \left(\frac{\tau_{active} + \tau_{inactive}}{\tau_{frame}}\right) \times \zeta(\tau_{PDCCH} + \tau_{PBCH})\frac{P_i|a_{si}|^2}{d^\alpha} + \sigma^2 \tag{7}$$

where τ_{active} and $\tau_{inactive}$ are the active and inactive period of the sensor node and τ_{frame} is the TTI of LTE frame.

4.3. Energy Consumption of Sensor Node

A sensor node in a network consumes its energy during four modes such as, during data transmission (E_{tx}), data receiving (E_{rx}), during idle listening (E_{idle}) and during sleep mode (E_{sleep}). Total energy consumed by a sensor node is the sum of all these energies. E_{tx} depends on the amount of transmitted data by nodes to other nodes as well as to the PAN coordinator. In the proposed work we does not include the energy model of the PAN coordinator and we assume that the PAN coordinator has sufficient energy source. In the reception mode, the sensor nodes receive data from the coordinator and the total energy consumed in this mode depends on the amount of data received by the sensor nodes. Nodes consume energy, when they are in idle listening mode by turning their transceivers in ON position without transmitting or receiving any data. The more time, a node remains in idle listening mode, more energy it consumes and can not be ignored in energy calculation. The sleep mode is the one in which the sensor turns off its receiver and a very minute amount of energy is consumed. Due to its very small amount, it has been ignored in our calculation. The accumulated energy (E_{Acc}) of a sensor node is calculated as:

$$E_{Acc} = E_{tx} + E_{rx} + E_{idle} \tag{8}$$

The energy consumed during the transmission mode can be given as

$$E_{tx} = E_{GTSREQ_{tx}} + E_{Data_{tx}} \tag{9}$$

where $E_{GTSREQ_{tx}}$ is the energy consumed during a GTS request transmission and $E_{Data_{tx}}$ is the energy consumed while transmitting a data packet. $E_{GTSREQ_{tx}}$ and $E_{Data_{tx}}$ can be further calculated as

$$E_{GTSREQ_{tx}} = V \times I_{tx} \times t_{tx} = V \times I_{tx} \times \frac{L_{GTS}}{R} \tag{10}$$

where V is the sensor battery voltage, I_{tx} is the current consumed during the transmission, L_{GTS} is the length of the GTS frame (equal to 9 bytes), R is the data rate in bits per second (bps).

$$E_{Data_{tx}} = V \times I_{tx} \times \frac{L}{R} \tag{11}$$

here, L is the data packet length in bits.

The energy consumption in the reception mode depends on the energy consumed during the beacon packet received by the sensor nodes. The length of the beacon packet depends on the number of nodes that have been allocated GTS and is given as:

$$E_{rx} = V \times I_{rx} \times t_{rx} = V \times I_{rx} \times \frac{L_{beacon}}{R} \tag{12}$$

where I_{rx} is the current required during the reception and t_{rx} is the receiving time that is the ratio of the length of beacon packet L_{beacon} and data rate R.

The energy consumed during idle mode is given as

$$E_{idle} = V \times I_{idle} \times t_{idle} \tag{13}$$

where I_{idle} is the current drawn during idle period. The duration of idle time t_{idle} depends on the superframe duration (SD) and time consumed during transmission and reception of data and it is calculated as:

$$t_{idle} = SD - t_{rx} - t_{tx} \tag{14}$$

By exchanging values of equations 10, 11, 12 and 13 in equation 8, the total energy consumed during a superframe is equal to:

$$E_{Acc} = V \left[(\frac{L_{GTS}}{R} + \frac{L}{R})I_{tx} + (t_{idle})I_{idle} + (\frac{L_{beacon}}{R})I_{rx} \right] \tag{15}$$

4.4. Residual Energy

Wireless sensor nodes are powered by the battery. The residual energy of a node is its current battery capacity. The remaining life of a node depends upon its residual energy. If residual energy of a node m before the start of k BI is E_k^m, then its residual energy during before the start of next BI E_{k+1}^m is calculated as:

$$E_{k+1}^m = E_k^m - E_{Acc-k}^m + E_{h-k}^m \tag{16}$$

here, E_{Acc-k}^m and E_{h-k}^m are energies consumed and harvested by node m in k_{th} BI. Energy of a WPAN before the start of k BI (E_k^{WPAN}) is the cumulative energy of all nodes in the WPAN. If WPAN comprises of n nodes, then WPAN energy just before the start of $k+1$ BI (E_{k+1}^{WPAN}) is calculated as:

$$E_{k+1}^{WPAN} = \sum_{i=1}^{i=k} (E_k^i - E_{Acc-k}^i + E_{h-k}^i) \tag{17}$$

Based on these residual energies of WPAN nodes, $E - MAC_{IoT}$ proposes two algorithms as:

- One for the whole WPAN, that adjusts the duty cycle based on residual energy of WPAN.
- To check the residual energy of each data requesting node and preferring a higher residual energy node to send its data during CFP over lower energy level nodes.

4.5. Duty Cycle Adjustment in $E - MAC_{IoT}$

In this section, an algorithm is proposed that allows the PAN coordinator to adjust its duty cycle by evaluating the overall energy of the WPAN (E_{PAN}) at the end of each SD. The algorithm allows the PAN coordinator to fine-tune the duty cycle of the next superframe without compromising the Quality of Service (QoS). The QoS is based on delay and number of collisions. The initial values of SO and BO are zeros.

If E_{PAN} is less than the threshold energy level then algorithm reduces the duty cycle of the next BI to increase the sleeping time of nodes to conserve more energy in the following way:

- If QoS is satisfied then it increases the BO without changing SO.

- If QoS is compromised due to increased collisions, then it needs to increase SO to increase the CAP duration with an increase in BO, so that the duty cycle should not increase.
- If QoS is compromised due to increased delay, then SO is reduced without changing the BO.

If E_{PAN} is in the permissible range, the algorithm only checks the QoS. In case QoS is satisfied then there will be no changes in the values of SO and BO. However, if QoS is compromised then SO and BO will be adjusted as:

- If QoS is compromised only due to increased delay, then both SO and BO will be reduced to decrease the BI time.
- If QoS is compromised only due to increased collisions, then SO will be increased to increase the active period along with an increase in BO.
- If QoS is compromised due to both collisions and delay, then SO is increased without changing BO.

These changes in parameter values of SO and BO are valid until they satisfy the standard's following limitations.

$$BO - SO \leq 10$$

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

A complete algorithm is shown in fig.3.

4.6. GTS Allocation Procedure in $E - MAC_{IoT}$

In this section, the second algorithm of $E - MAC_{IoT}$ is proposed that allows the PAN coordinator to scrutinize GTS requesting nodes to send their data during GTS. This GTS allocation procedure in $E - MAC_{IoT}$ is based on individual energy level information of each requesting node and its amount of data traffic.

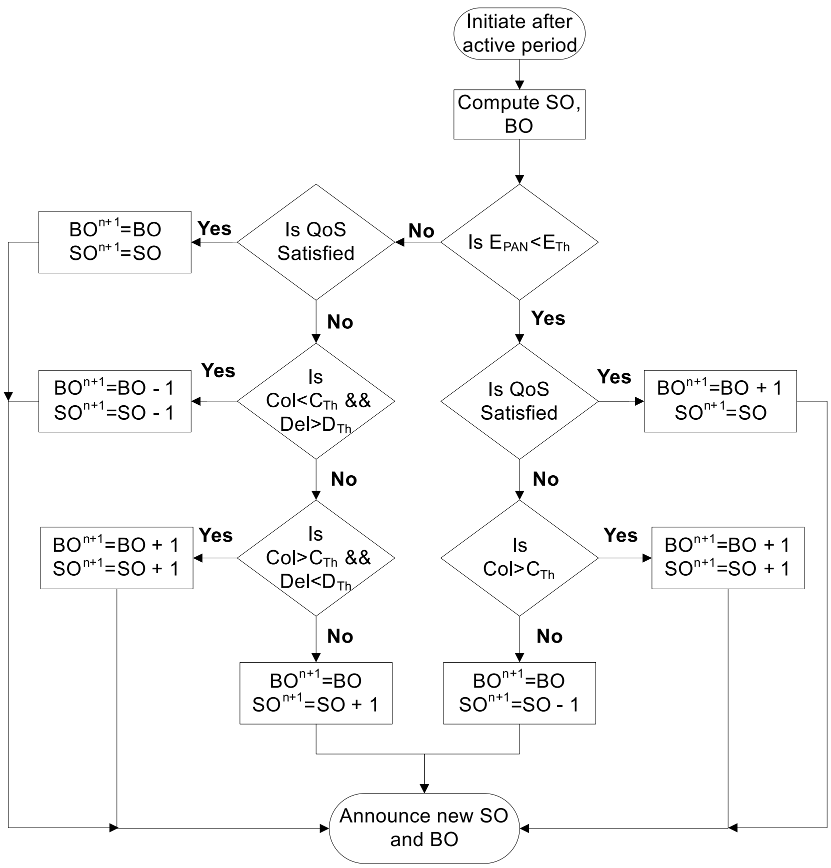

Figure 3: Adaptive duty cycle algorithm

4.6.1. Energy Level Information

In the proposed protocol, GTS requesting nodes to use the standard GTS request frame to request for GTS. The requesting nodes determine the number of GTS required to send information by knowing the data and the slot capacity S_{cap} given as

$$GTS_{req} = Data/S_{cap} \tag{18}$$

In the GTS request frame, the starting 2 bytes define the control frame as shown in Fig. 4. In this figure, the bits b_7, b_8, and b_9 of the control frame of the GTS request frame are highlighted. These three bits were not used in the standard and were reserved for future work. That's why, in this work, these three bits are used to send nodes energy levels to the coordinator. These three bits allow nodes to divide the residual energy into 8 different levels as shown in Table 2. The coordinator allocates GTS to the requesting nodes by considering these energy levels.

Table 2: Residual Energy Information

Energy Information Field Value	**Energy Level**
000	Residual energy is < 12.5 %
001	Residual energy is ≥ 12.5 % & < 25 %
010	Residual energy is ≥ 25 % & < 37.5 %
011	Residual energy is ≥ 37.5 % & < 50 %
100	Residual energy is ≥ 50 % & < 62.5 %
101	Residual energy is ≥ 62.5 % & < 75 %
110	Residual energy is ≥ 75 % & < 87.5 %
111	Residual energy is ≥ 87.5 % & < 100 %

4.6.2. GTS Alloaction in $E - MAC_{IoT}$

In the IEEE 802.15 4 standards, the coordinator allocates GTS on First Come, First Serve (FCFS) basis without considering their energy levels. This could deplete the energy of some nodes, hence disconnecting them with the rest of the network. In the proposed protocol, the life cycle of the network is improved by scheduling prioritized transmissions to those GTS requesting nodes that have a higher energy level. This also allows nodes with lower energy consumption to harvest energy in the meantime and improve their battery residual energy.

To efficiently allocate GTS, the $E - MAC_{IoT}$ uses a knapsack optimization algorithm. Knapsack algorithm allows optimally collection of valuable items from the different available items up to its carrying capacity. The analogous mapping of this problem to select the GTS requesting nodes for slot allocation

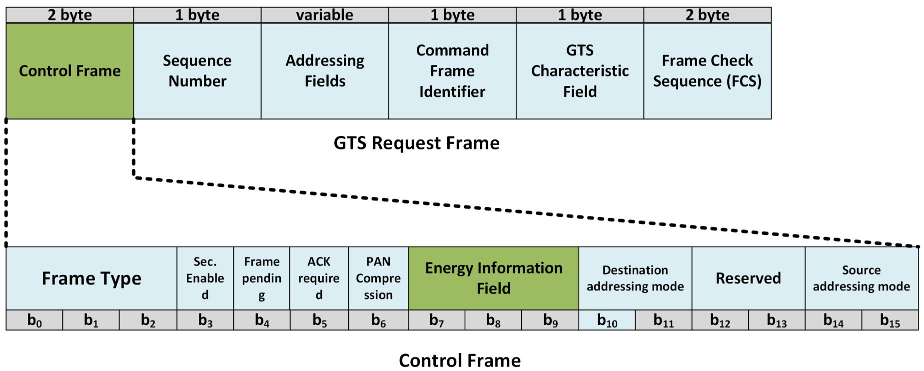

Figure 4: GTS Request Frame Format

Table 3: Mapping of GTS allocation problem to knapsack problem

	GTS utilization with increased life cycle	**Knapsack problem**
M	Maximum number of available slots	Carrying capacity of knapsack
b	GTS requesting nodes to be satisfied GTS	Items to be packed
W_b	GTS requested by a node	weight of an item
P_b	Residual energy of a node	value of an item

is shown in Table 3. Here, the coordinator has to allocate the available GTS M to the GTS requesting nodes b in such a way that nodes with higher residual energy P_b should be preferred for transmission. In this problem, the weights and the values of requesting nodes are the numbers of slots requested and the residual energy respectively. Optimal GTS allocation to the maximum number of nodes with higher energy levels to send their data can be mapped with the 0-1 Knapsack problem.

Knapsack allows us to select the most valuable items from the available list of items to fill its capacity. In our problem, knapsack allows us to optimally scrutinize those GTS requesting nodes which have better residual energies at the cost of more computation. Our problem for optimal selection of nodes by considering their residual energy levels are mapped with 0-1 knapsack problem as:

Let W_b be the number of GTS requested by a node. If $W_b \leq$ M, then the sink allocates GTS to all GTS requesting nodes by applying the shortest job first algorithm [34]. If $W_b >$ M, then the sink examines the nodes that request the GTS by applying the knapsack algorithm.

Table 4: Knapsack Table

Sensor Nodes	**Maximum GTS Slots (7)**							
	0	1	2	3	4	5	6	7
	0	0	0	0	0	0	0	0
B	0	8	8	8	8	**8**	8	8
A	0	8	8	16	16	16	**16**	16
C	0	8	8	16	16	16	16	**21**
E	0	8	8	16	16	16	16	21
D	0	8	8	16	16	16	16	21

Suppose there are 5 sensor nodes A, B, C, D, and E, which requested for 2, 1, 4, 5, and 4 CFP slots along with their residual energy levels to the coordinator as 8, 8, 5, 2, and 4 respectively. It means there are 16 GTS requests against 7 GTS available in an SD.

As the number of requesting nodes is more than the available capacity, that is why, the coordinator has to scrutinize some nodes optimally by applying the knapsack optimization algorithm. The algorithm scrutinizes successful nodes by filling a knapsack table as follows:

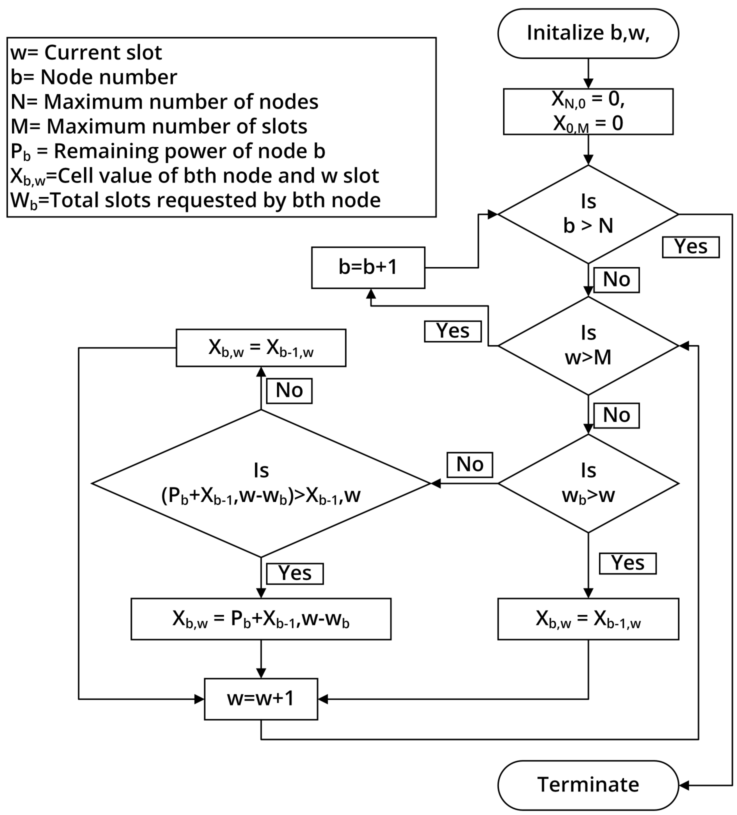

Figure 5: Knapsack table filling algorithm

1. Number of rows and columns of the knapsack table comprises the total number of GTS requesting nodes and GTS capacity respectively. The first row and first column of the table are initialized by all zeros.
2. Before filling the table, all the requesting nodes are placed in ascending order. That is, nodes with fewer GTS requesting slots fill their row ahead

of other nodes as shown in Table 4.

3. Each cell ($A[i, j]$) of the requesting node A is filled with its immediate upper cell value ($A[i-1, j]$) till its requesting slots are more than current slot capacity. Otherwise, the cell will be filled with the value of $A[i-1, j]$ or sum of residual energy of that node and the value of a specific cell in the upper row.

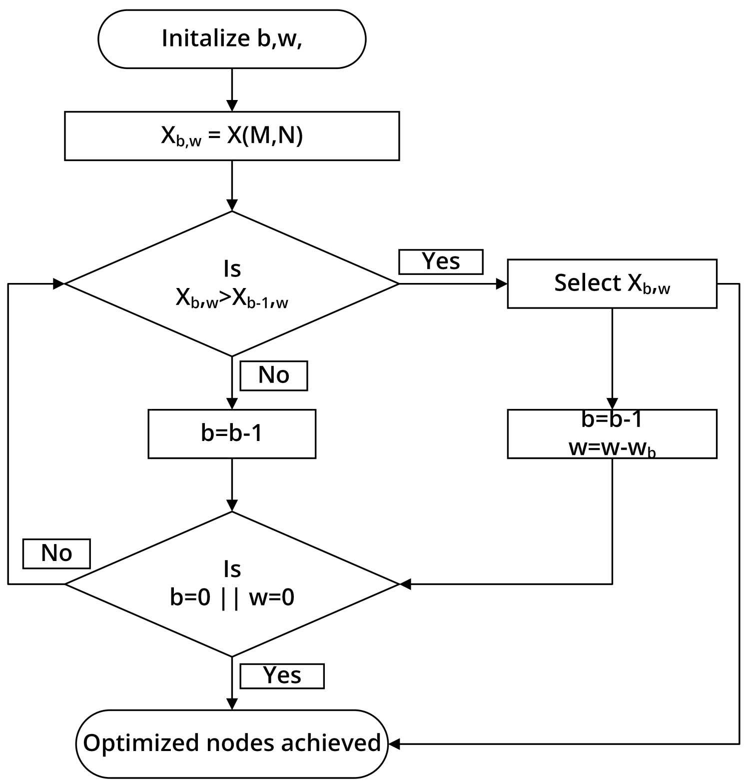

Figure 6: Optimal node selection algorithm

A complete algorithm to fill the knapsack table is shown in Fig. 5. The coordinator scrutinizes the nodes optimally by simply comparing the cell value with its upper cell value as described in the node selection algorithm shown in Fig. 6. A knapsack table for the given example is filled as shown in Table 4. Nodes A, B, and C are selected optimally in the given example due to their residual energy levels.

5. PERFORMANCE EVALUATION

To evaluate the performance of $E - MAC_{IoT}$, a simulation environment is created as shown in Fig. 3 using MATLAB. We randomly deployed 15 sensor nodes within a radius of 100 m from the LTE eNodeB. The distance between the sensors nodes and the coordinator is kept 50 m. For the propagation model, we use the two ray ground path loss model with a path loss exponent value of 2 and Rayleigh multipath fading. The transmit power of the LTE eNodeB is taken as 20 dBm, and the downlink channel frequency is 1.25 MHz. The simulation parameters are listed in Table. 5.

Table 5: Simulation Parameters

Parameter	**Value**
LTE eNodeB Tx Power	20 dBm
Data Range (bytes)	20 - 120
Carrier frequency (IoT network)	2400 MHz
Data rata (R)	250 kbps
Battery	3 V
Sleeping current	0.001 mA
Receive current	19.7 mA
Transmit current	17.4 mA
LTE TTI	40 ms
LTE frame duration	10 ms
RF to DC efficiency	0 - 0.7

Sensor nodes generate data requests for transmission to the coordinator one by one i.e., the data generation request of the first sensor arrives first followed by the second sensor and so on. The number of GTS request by each sensor node is selected randomly. Based on the data requests and the shared energy level information by the sensor nodes, the coordinator runs the proposed protocol for

GTS allocation. We compare our proposed protocol with the standard IEEE 802.15.4 MAC.

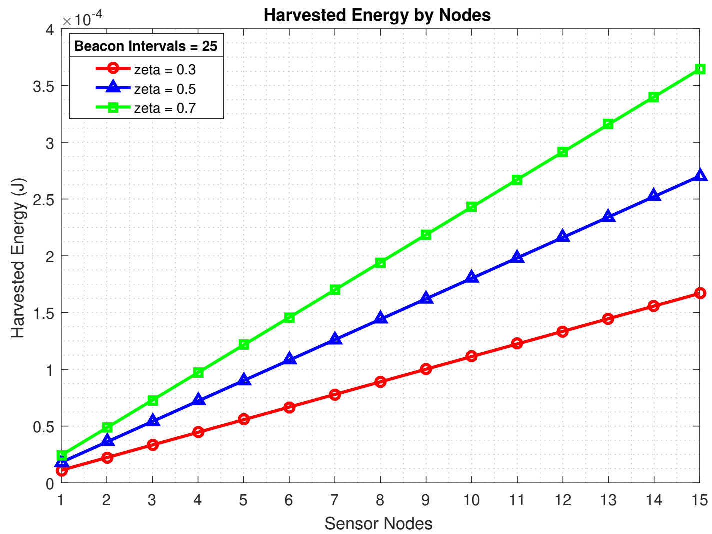

Figure 7: Effect of RF-to-DC rectification efficiency on the harvested energy

We first analyze the amount of energy harvested by the sensor nodes in the considered network scenario. In Fig. 7, the effect of RF-to-DC rectification efficiency (ζ) on harvested energy is shown for 25 beacon intervals considering three different values of ζ having same value of SO and BO. The SO and BO values are kept same to analyze the effect of ζ on harvested energy for proposed scheme. When the value of ζ is 0.3, the accumulated harvested energy by sensor nodes is 165 μJ. As we further increase ζ to 0.5 and 0.7, the accumulated harvested energy is increased to 270 and 364 μJ respectively. Thus, the value of (ζ) directly impacts the amount of energy harvested during a certain period.

In Fig. 8 the impact of SO and BO values on harvested energy for 25 beacon intervals is shown. The SO and BO values determine the length of an active and inactive period of the total beacon interval.The duty cycle of a node is calculated as the ratio between the amount of time a node remains inactive period and the total time duration in a beacon interval. As in the proposed

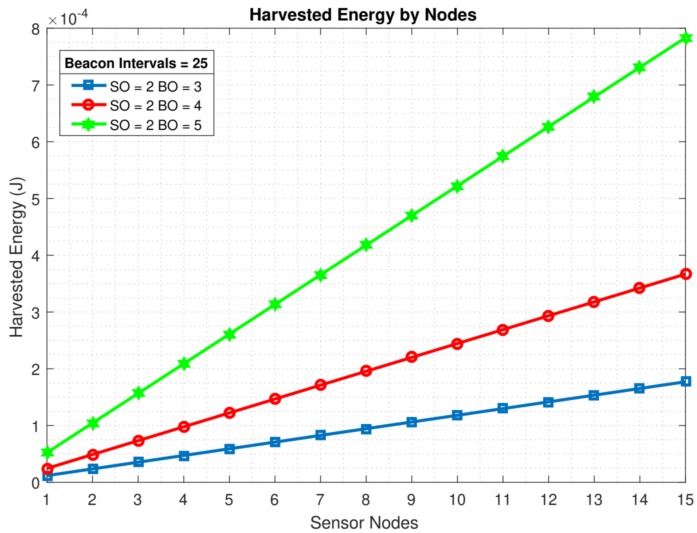

Figure 8: Effect of IoT sensor node's duty cycle on the harvested energy

scheme the sensor node harvest energy during the active and inactive period of the beacon interval so when the value of the SO and BO is 2 and 3 respectively corresponding to a 50% duty cycle, the amount of accumulated harvested energy is up to 177 μJ. When we further increase the value of BO to 4 the inactive period is increased providing more time for the sensor to harvest energy thus the accumulated harvested energy is increased up to 366 μJ whereas, for the case of SO = 2 and BO = 5 with 12.5% duty cycle, the harvested energy is increased up to 783 μJ.

Fig. 9 illustrate the average harvested energy at the IoT sensor nodes between standard and proposed for different values of SO and BO. It is evident from the graph that the proposed scheme outperforms the standard for different values of SO and BO. When the value of SO and BO is 2 and 3 respectively the accumulated harvested energy for the standard is 127 μJ while in the case of the proposed scheme is 261 μJ. As we further increase the value of SO and BO to 3 and 4 respectively the harvested energy for the standard is increased to 228 μJ and for proposed the harvested energy is increased up to 364 μJ. The

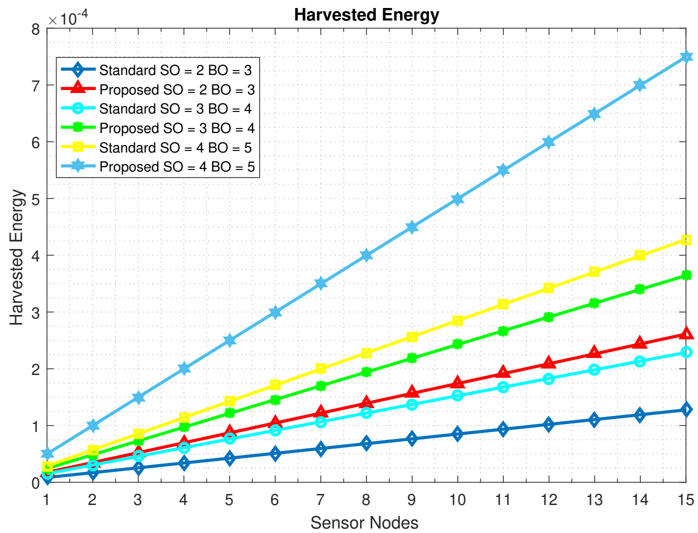

Figure 9: Average Harvested energy at IoT sensor nodes

standard uses the FCFS algorithm resulting in quick depletion of batteries thus the average harvested energy is low as compared to a proposed scheme that provides balanced energy consumption.

The results shown in Fig. 10 compares the performance of $E-MAC_{IoT}$ with the IEEE 802.15.4 standard in terms of energy consumption by the sensor nodes. As illustrated in the bar graph, the energy consumption in the standard for the first seven sensor nodes is higher than other nodes in the network. The reason is that the coordinator allocates GTS to the first four nodes more frequently because their data requests were received earlier. Based on the FCFS algorithm, the first four nodes get prioritized transmissions resulting in quick exhaustion of their batteries as compared to the other sensor nodes. On the other hand, in $E - MAC_{IoT}$ the coordinator selects the nodes having higher energy levels and avoids GTS allocation to the nodes having low energy levels. As a result, $E-MAC_{IoT}$ provides balanced energy consumption of all the sensor nodes, not causing any single sensor to deplete energy quickly.

Fig. 11 depicts the residual energy of all sensor nodes in the network for the

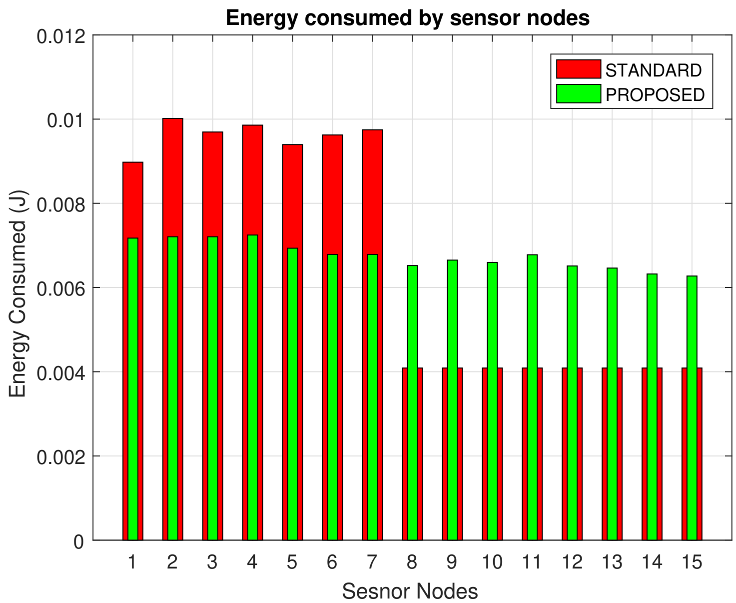

Figure 10: Energy consumption of the IoT sensor nodes

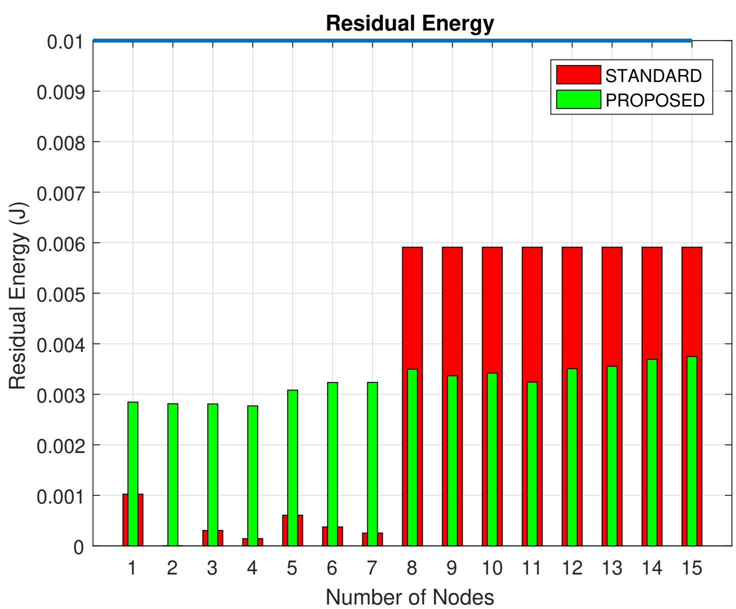

Figure 11: Residual energy of the IoT sensor nodes

standard protocol and $E - MAC_{IoT}$. The initial energy of each sensor node was 0.1 joule. As the standard scheme allocates GTS on a FCFS basis, thus the residual energy of the first seven sensors are almost depleted. However, in $E - MAC_{IoT}$, residual energy of all nodes is available because knapsack prefers nodes with more residual energy to send their data over other nodes.

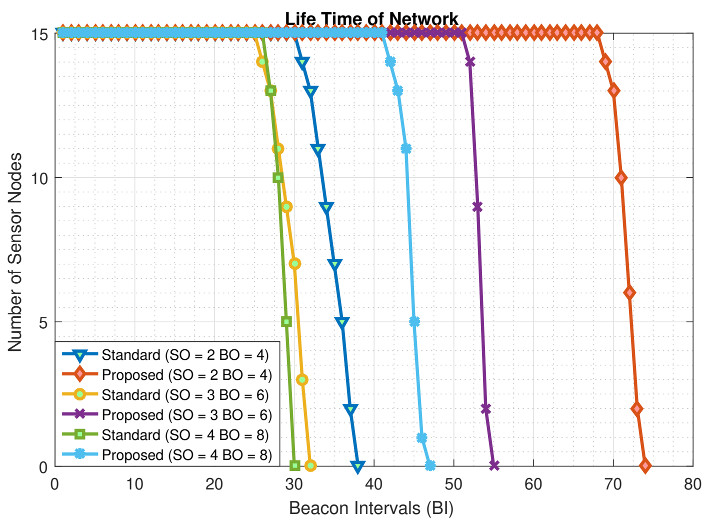

Figure 12: Life time of IoT sensor nodes

Fig. 12 shows the number of sensor nodes when their energy depletes at a particular BI. We consider the BI value at which the battery of all the sensor nodes gets depleted as the battery lifetime of the IoT network. We show the results for the standard and $E - MAC_{IoT}$ for three different duty cycle values. For the standard protocol, the battery of all sensor nodes depletes within 38 BI for all three duty cycles. In comparison, $E - MAC_{IoT}$ extends the battery lifetime of the sensor nodes by $17 - 38$ BI. This highlights a key advantage of the proposed protocol which is to improve the battery lifetime of the IoT network.

Fig. 13 depicts the total data transmitted by the sensor nodes at different beacon intervals for three different values of SO and BO. It can be seen that $E - MAC_{IoT}$ can transmit 17-19.5 kilobytes more data as compared to the standard protocol within 90 BI. This is because the battery depletion rate in

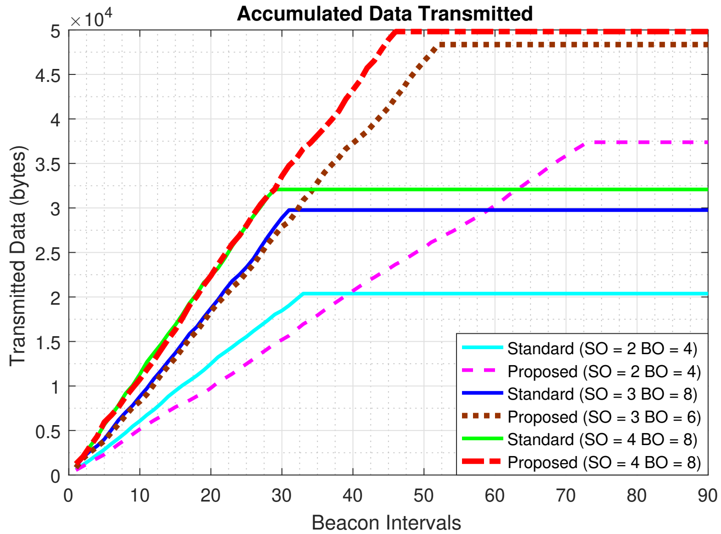

Figure 13: Data transmitted at different beacon intervals

the standard protocol is higher, thus resulting in a few sensor nodes to turn off. On the other hand, $E - MAC_{IoT}$ provides balanced energy consumption and thus higher data throughput.

6. Conclusion

Energy-efficient GTS allocation with improved life cycle and better data transmission are major limitations in RF energy harvesting based IoT networks. IEEE 802.15.4 standard is widely used for medium access control in IoT networks. However, its data transmission during GTS results in unbalanced power consumption among nodes and less GTS utilization. The proposed protocol overcomes these limitations by adapting the duty cycle of IoT devices by considering their energy without compromising the QoS. Besides, it prefers higher residual energy nodes to send their data as compared to low energy nodes. The proposed protocol scrutinizes GTS requesting nodes optimally by modified knapsack algorithm. The algorithm adjusts nodes to allocate maximum available GTS and hence increases the throughput of the network. Those nodes, which were not allowed to send their data remain in sleep mode to harvest more energy and increase their energy levels and consequently, a close uniformity in the residual energy of all nodes is maintained. This increases the life cycle of the IoT based network. Simulation results show that the proposed protocol not only improves the life cycle of the IoT based sensor networks but also allowing 19.5 kB more data to be transmitted as compared to the standard protocol.

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