D-MAC: A Dynamic MAC Algorithm for the Body Area Sensor Networks Based on IEEE 802.15.4

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Summary
Wireless Body Area Network (WBAN) is a wireless sensor technology used to connect small nodes with sensing abilities to collect necessary information. IEEE 802.15.4 is commonly adopted for WBAN because of its low duty cycle and low power operation. WBAN data is communicated in a superframe structure defined by IEEE 802.15.4 beacon enabled mode. Superframe structure predominantly based on beacon order (BO) and superframe order (SO). BO depicts time interval of beacon whereas, SO defines duty cycle of connected WBAN source nodes. Optimal values selection of both BO and SO is crucial in WBAN, because these values have impact on energy consumption, latency of communication, synchronization, association and throughput. Presently, IEEE 802.15.4 uses fixed BO and SO values. In this research paper, we recommend a Dynamic MAC (D-MAC) algorithm for the WBAN to adapt both BO and SO simultaneously to enhance network life time, network throughput and decrease latency of communication. Detailed simulation analysis show that D-MAC outperforms IEEE 802.15.4 and other well-known algorithms in relations of delay, energy consumption and network throughput.
Key words:
WPAN, dynamic duty cycle, beacon enabled mode, wireless body area networks

1. Introduction

Low rate wireless personal networks (LR-WPAN) [1] is primarily intended for low power networks. LR-WPAN is widely adopted for wide range of application; surveillance [2], health care [3, 4], home automation [5], agriculture [6, 7] and industrial automation [8, 9] because of its applicability and low power consumptions.
WBAN is a form of WPAN which have vital significance in health monitoring. WBAN is a wireless network, which joins in and on body sensors and form a self-configurable network [10, 11]. These sensors are used to collect information that can be given to the care taker for monitoring the health of patient. WBAN in-body application includes monitoring and Implantable Cardiac Defibrillator (ICD) [12]: a small device which is used to monitor the heart rhythms, control of bladder function, Continuously Glucose Monitoring (CGM). WBAN on-body applications include monitoring of glucose, blood pressure and temperature. The nature of data reported by BAN devices can be on-demand, emergency and periodic. On-demand traffic can be used by the doctor for the diagnostic purpose. This is further divided into periodic data traffic and continuous data traffic. Periodic traffic can be sent by the sensor after some interval of time, possibly when a node have some data to send (when information is required occasionally), Continuous traffic is sent by the sensor node continuously; such as Continuous Glucose Monitoring (CGM). Emergency traffic is totally unpredictable, which is initiated by sensor nodes when an activity is observed. Normal traffic is used for routine health monitoring having no critical time bound requirements. Detailed WBAN applications are given in table 1 along with their QoS attributes.

TABLE 1: WBAN application and their QoS attributes

Sensor Node	Topology	Data rate	QoS (Sensitive to latency)	Power consumption
Blood glucose	Star	Few kbps	Yes	Extremely low
Blood pressure	Star	<10 kbps	Yes	High
SpO_2	Star	32 bps	Yes	Low
ECG	Star	3 kbps	Yes	Low
EEG	Star	Few kbps	Yes	Low
Pulse oximetry	Star	Few kbps	Yes	Low

WBAN network can be formed by the use of full function devices (FFDs) and reduced function devices (RFDs). FFDs can form any topology (star or peer-to-peer) and can communicate other connected device. Whereas, RFDs only talk to the PAN coordinator. Due to limited functionalities it cannot become a PAN coordinator. Figure 1 shows IEEE 802.15.4 supported topologies to form a complete WPAN.

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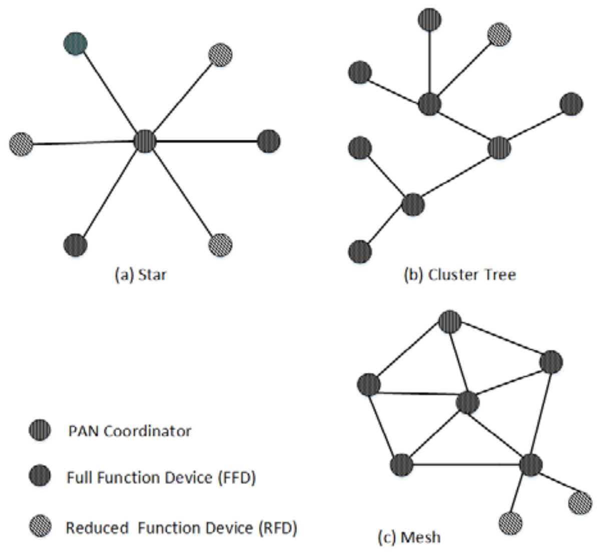

Fig. 1. Supported topologies of IEEE 802.15.4

In LR-WPAN, the central node usually called "PAN Coordinator" determines the duty cycle of nodes in a star topology [13]. To achieve greater performance, nodes synchronization and association, optimal values of both BO and SO should be chosen carefully. The duty cycle of nodes can be dynamically adapted by concurrently adjusting both BO and SO according to the nature of data traffic. However, IEEE 802.15.4 does not propose any algorithm that can schedule the BO and SO dynamically to meet the WBAN requirements. In this work, we present a Dynamic MAC (D-MAC) for WBAN applications to adjust the BO and SO at the same time to achieve enhanced network performance.

This research paper is structured as follows: existing research efforts on BO and SO dynamic scheduling in WBANs is presented in section 2. Section 3 outlines the LR-WPAN IEEE 802.15.4 overview. Section 4 describes the D-MAC algorithm in depth. Detailed results and analysis are discussed section 5, while last section completes this paper.

2. Related Work

The existing super-frame adaptation schemes and their impact on network performance is discussed in this section. In [14], maximum network throughput and end-to-end delay of communication for the IEEE 802.15.4 are studied. However, only a single transceiver and sender is studied in this mathematical model based research effort. The performance assessment for WBANs is analyzed based on IEEE 802.15.4 standard in [15]. In [15], the primary goal of analysis assessment is based on energy consumption. In [16], the performance assessment for BAN application is assessed in a star topology with 16 number of source nodes based on IEEE 802.15.4. Also, interference is studied in detail along with its mitigation in this research. Algorithm presented in [17] schedule the duty cycle of nodes by changing only SO parameter while BO is kept constant. In this algorithm, PAN coordinator computes occupancy ration of superframe and collision ratio. The PAN coordinator then compares the computed values to some pre-defined thresholds and alters the duty cycle of nodes accordingly. Another SO adaptation algorithm is presented in [18], the central device dynamically adjusts the SO primarily based on queue size, network life time and date rate. Due to fixed BI energy consumption increases if low value of BO is used. Therefore, frequently beacons are transmitted results in low throughput and packet drop ratio.

The WBAN network performance can also be optimized by changing both SO and BO MAC parameters simultaneously [19, 20]. Duty cycle self-adaptation algorithm (DBSAA) [19] alters super-frame structure simultaneously by considering; CAP Occupancy Ratio (OR), Collision Rate (CR) and received packets by PAN coordinator. However, DBSAA adopts the same data rate for all kinds of applications. In our previous work done, Traffic Aware Dynamic Super Adaptation Algorithm (TDSAA) [20] tries to schedule the superframe structure by dynamically adapting both BO and SO based on star topology in IEEE 802.15.4 networks. TDSA algorithm adjusts the superframe structure based on application specific data rate, receive ratio at the PAN coordinator and number of transmitting nodes. TDSA follows three steps; it estimates network load to calculate the expected SO, secondly it determines changes in the network load, thirdly it should for a number of BI interval before the algorithm is triggered. DBSAA [10] and TDSAA [20] displays improved performance in relations with network throughput, latency of communication and network life time by dynamically adapting both BO and SO parameters. The proposed D-MAC algorithm differs from our previous work TDSAA [20] because a delay metric is added that is necessary for WBAN applications such as ECG and pacemaker, besides buffer size is taken into consideration for accessing the contention level within the BAN. Another model called sub hub [21] proposed for WBAN based IEEE 802.15.4. The main objective of this model is to prevent nodes disassociation. Therefore, unified assignment technique among MaH (Main hub) and SuH (Sub hub) is compulsory to prevent association problem.

3. Superframe Structure Overview

In this section, IEEE 802.15.4 based superframe structure is discussed in detail which is mainly adapted for LR-WPANs. An important feature of IEEE 802.15.4 is the low power depletion which is achieved by a low duty cycle operation. For resource allocation the PAN coordinator divides the time into series of superframes. As shown in figure 2 the superframe structure is bounded by beacon periods of equal length. Superframe duration consists of mainly on two parts; active and inactive period. In active period the PAN coordinator and source nodes stay awake all the time. It is further divided into Contention Access Period (CAP) and Contention Free Period (CFP). If the devices has data to send they contend for the free slot to send data to the PAN coordinator in CAP period. However, CFP is an optional mode of communication in IEEE 802.15.4. Whereas, in the inactive period the devices stay in sleep mode (low power mode) when the devices has nothing to send.

The duty cycle of end devices are defined by the two MAC bounds: the BO and SO. The size of beacon interval (BI) is defined by BO whereas, the SO depicts the length of active superframe duration within each BI. BI, SD, DC and sleep period of superframe structure can be computed by the below equations.

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

$$BI = aBaseSuperframeDuration \times 2^{BO} \quad (0 \leq B0 \leq 14) \quad (2)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (0 \leq B0 \leq 14) \quad (3)$$

$$DC = \frac{SD}{BI} \quad (4)$$

For example, in case when BO is 7 and SO is 6 the aforementioned equations yields the DC as 50%.

aBaseSuperFrameDuration = 60 × 16symbols = 960symbols

BI = 960 × 2^7 = 1966.08ms

SD = 960 × 2^6 = 983.04ms

Sleep Period = BI – SD = 983.04ms

DC = 0.5

Slotted CSMA/CA is used by beacon enabled mode for channel access and data transmission. In beacon enabled network the "slot" concept is used. As shown in figure 2, there are 16 slots of equal length. The elementary element called the backoff period primarily used to identify the most suitable time in each slot, and it is represented by aUnitBackoffPeriod symbol (a time duration that a device must wait before accessing the channel).

According to Eq. (5), length of a single slot duration for SO = 1 is obtained as follows:

$$T_{SDslot} = \frac{SD}{16} \quad (5)$$

$$T_{SDslot} = \frac{60 \times 16 \times 2^{SO}\ Symbols}{16} = 60 \times 2^{SO}\ \text{Symbols} = 3.84\ \text{ms} \quad (6)$$

$$N_{BOP} = \frac{T_{SDslot}}{T_{BOP}} = \frac{60 \times 2^{SO}\ Symbols}{20\ Symbols} = 3\times 2^{SO} = 6 \quad (7)$$

Eq. (7) is used to compute the total backoff periods in each single slot duration. Whereas, T_{BOP} is the time required for a single backoff period, which is aUnitBackoffPeriod=20 symbols. Therefore, the total backoff in each slot is 6, while a CAP enables 786,432 backoff periods when SO is set at 14.

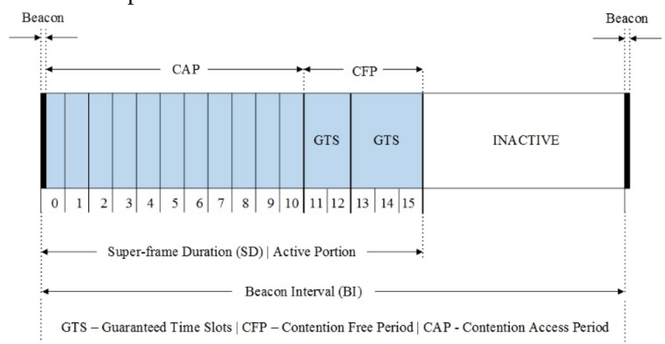

Figure. 2. The Superframe structure

4. Methodology and Operation of D-MAC Algorithm

This section describes the D-MAC algorithm in detail. The proposed D-MAC algorithm works in a star topology beacon enabled mode. This work only considers the active portion while, GTS is not used. In D-MAC, it is assumed that PAN coordinator know about the traffic nature in BAN delivered by different sensors. In BAN energy and delay are the primary concerns and their performance can be optimized by the appropriate selection of BO and SO.

The primitive task of D-MAC algorithm is based on the calculation of Projected SO (P_{SO}) as shown in Eq. 8. P_{SO} is the projected size of SD for the next beacon interval. It is estimated at the expiry for every BI.

$$P_{SO} = (SN \times SD \times Pkt_{size} \times T_{time}) \times T_{delay} \quad (8)$$

$$T_{time} = \frac{Pkt_{Size}}{250} \quad (9)$$

$$T_{delay} = T_{ack} + Ack + T_{IFS} + (2 \times CCA) + BOP \quad (10)$$

$$RR = \left[\frac{Total_{pkt}}{SN \times SD}\right] \times 100 \quad (11)$$

In Eq. (8), *SN* are the total number transmitting nodes where, *SD* is based on the number of packets that a single node generates during the current superframe duration and Pkt_{size} is a single packet size in bits. Eq. (9), calculates the time needed for a single packet transmission from source to destination in 2.4 GHz range. Estimated transmission delay is computed by eq. (10) for a single packet including *Ack*. Table 1 shows the standard values for eq. (10) calculation. Eq. (11) is used to compute the receive ratio at PAN coordinator where, $Total_{pkt}$ represents the number of received packets.

Table 2. Parameters and their default values

Parameter	Value
T_{ack}	864 µs
Ack	352 µs
T_{IFS}	192 µs
Clear Channel Assessment (CCA)	128 µs
The Backoff Period (BOP)	32 µs

D-MAC algorithm is triggered by the PAN coordinator to adjust the superframe structure by simultaneously adapting the optimal values of BO and SO based on network traffic generated by PAN source nodes and buffer size. During the idle network operation, D-MAC uses a default setting of BO (BOdefault = 6) and SO (SOdefault = 2). Symbols used in algorithm 1 and algorithm 2 are listed in table 3 along with their description.

Table 3. Symbols and their description used in D-MAC algorithm

Symbols	Description
P_{SO}	Project SO estimated for the current interval
SO_{cur}	Current SO being used for previous interval
$SO_{default}$	Minimum limit of SO, value set at 2
BO_{max}	Maximum limit of BO, value set at 10
BO_{cur}	Current BO being used for previous interval
$BO_{default}$	Minimum limit of BO, value set at 2
$BCN_{interval}$	Number of interval the coordinator should wait to trigger the algorithm
β	Number of wait interval, the algorithm should wait for
RR	Received ratio, calculate at PAN coordinator
RR_{th}	Maximum limit of received ratio at PAN coordinator
OBS_{delay}	Delay observed at PAN coordinator for each beacon interval
REQ_{delay}	Application specific delay

Projected SO algorithm first calculates the estimated SO for the next beacon interval. After PSO calculation, if PSO is less or equal to default SO or no network activity is observed then communication is done with default settings to conserve more energy. The detailed functions of projected SO is listed in Algorithm 1.

Algorithm 1. Projected SO Algorithm

After every beacon interval
P_{SO} is calculated using Eq. 8
IF $P_{SO} \leq SO_{default}$ OR no communication **THEN**
    $SO_{cur} \leftarrow SO_{default}$
ELSE
    $SO_{cur} \leftarrow P_{SO}$
END IF

After the selection of P_{SO} for the next interval, it is further checked for appropriateness as shown in Algorithm 2. In case, P_{SO} is greater than previously used SO and greater $BO_{default}$ the P_{SO} is simply assigned to BO_{cur}. If SO_{cur} is less than or equal to $SO_{default}$ then network load is verified when beacon interval reaches β. *RR* is then compared with application defined threshold. Then, the observed delay is compared with required delay, if OBS_{delay} is greater or equal to REQ_{delay} then, D-MAC algorithm gradually increment SO_{cur}. As a result, it will enhance the packet delivery and will also decrease the delay guaranteed requirements. Otherwise, SO_{cur} is decremented by 1 to conserve energy consumption.

On the other hand, when receive ratio is less, which might indicate collision is happened due to high contention of nodes competing at the same time for communication channel as a result, reduction in receive ratio observed. In this scenario, the delay observed in communication is compared with required delay, if OBS_{delay} is greater or equal to REQ_{delay} then, D-MAC algorithm increment SO_{cur} by 1 to decrease the delay observed. Otherwise, transmission is carried out with SO_{cur} when no changes observed in the network.

Algorithm 2. D-MAC Algorithm

After every beacon interval expiry
IF $P_{SO} > SO_{cur}$ AND $P_{SO} > BO_{default}$ **THEN**
    $BO_{cur} \leftarrow P_{SO}$
END IF
IF $BCN_{interval}$ % β == 0 **THEN**
    IF $RR \geq RR_{th}$ then
        IF $OBS_{delay} \geq REQ_{delay}$ and $SO_{cur} < BO_{max}$ **THEN**
            $SO_{cur} \leftarrow SO_{cur} + 1$
        ELSE
            $SO_{cur} \leftarrow SO_{cur} - 1$
        END IF
    ELSE
        IF $OBS_{delay} \geq REQ_{delay}$ and $SO_{cur} < BO_{default} + 1$ **THEN**
            $SO_{cur} \leftarrow SO_{cur} + 1$
        END IF
    END IF
END IF

5. Performance Evaluation

This section describes the D-MAC, IEEE 802.15.4 and other well-known algorithms performance evaluation for WBAN applications based on NS2 [22]. WBAN application requirements considered during simulation and their contents information along with network size and network life time. Figure 3 describes a typical WBAN infrastructure based IEEE 802.15.4 with in a hospital scenario, which shows multiple sensors installed on a human body connected with a PAN coordinator. These sensors are used to collect information that can be used by care givers to monitor the health of the patient. We consider a star topology network and nodes communicate with PAN coordinator in a beacon enabled network. The coordinator is placed in the centre of WBAN. The BO and SO used for IEEE 802.15.4 based simulation is 6 and 2-5 respectively, that is being used by many commercially available PAN devices [23]. In the following simulations BO=6 and SO=2 is used by D-MAC as default BO and SO initially. General simulation settings are presented in table 4. The performance is analyzed in two scenarios: continuous data reporting and periodic data reporting. In the former nodes continuously send data to the PAN coordinator during simulation time whereas, in the latter nodes periodically transmit data for certain duration only.

5.1 Periodic Data Reporting

In order to further investigate the performance of D-MAC, we use a scenario where nodes periodically transmit data for a certain interval then stop data reporting. This process is repeated several times to observe whether D-MAC is capable of adjusting duty cycle immediately as network traffic starts.

The average throughput D-MAC and IEEE 802.15.4 alongside simulation time is shown in figure 4. When the simulation starts the network load is gradually increased by turning ON source nodes, as a result throughput of both D-MAC and IEEE 802.15.4 increases slowly. It is evident that at BO=6, SO=4 the duty cycle of nodes is high and CAP duration is more as a result the performance of IEEE 802.15.4 is better. However, D-MAC outperforms IEEE 802.15.4 because of its dynamic behavior.

Figure 5 presents the scenario of end-to-end latency at the PAN for D-MAC and IEEE 802.15.4. By using fixed SO parameters, IEEE 802.15.4 produces higher end-to-end latency in case of BO=6; SO=2, 3 and 4. On the other hand, D-MAC achieves lower latency, stable and cost effective performance because of its dynamic duty cycle adjustment.

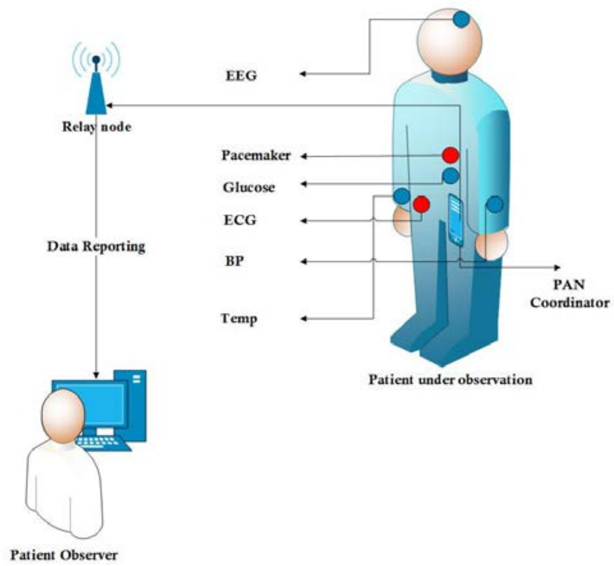

Figure. 3. Typical WBAN Infrastructure

Table 4. Simulation parameters

Parameter		Value
Simulation time		900 s
Range of WBAN		15 m
Frequency		2.4 GHz
D-MAC	$BO_{default}$	6
	$BO_{maximum}$	10
	$SO_{default}$	2
	$SO_{minimum}$	2
IEEE 802.15.4	Beacon order	6
	Superframe order	2,3,4,5
Traffic type		CBR
Interface queue length		30
Packet size in bytes		60
Source nodes		2, 4, 6, 8, 10
Data rata in kbps		50, 100, 150, 200
Primary energy		4 Joules
Tx mode		12.3 mA
Rx mode		14 mA
Sleep mode		0.02 µA
Idle mode		0.4 mA

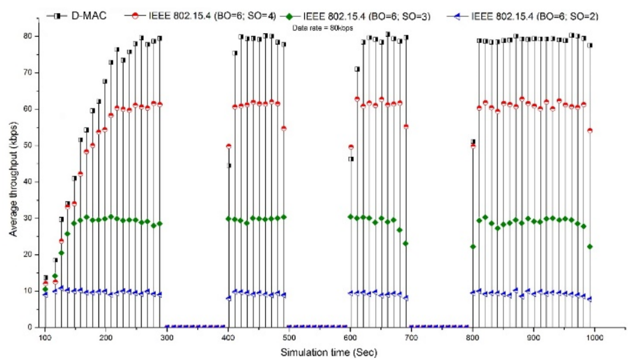

Figure. 4. Throughput of D-MAC and IEEE 802.15.4 with respect to simulation time

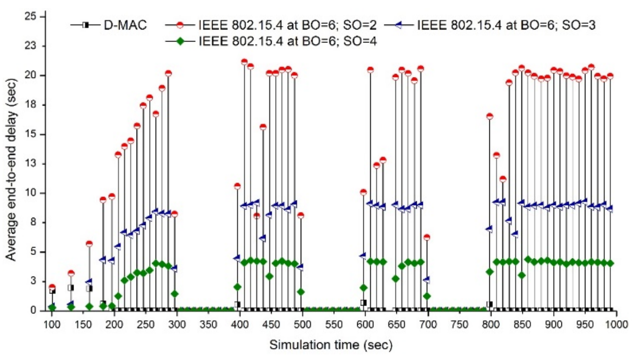

Figure. 5. End-to-end latency of D-MAC and IEEE 802.15.4 with respect to simulation time

5.2 Continuous Data Reporting

Furthermore, D-MAC performance is evaluated for a scenario where nodes continuously transmit data. This scenario is repeated for D-MAC to observe throughput, average end-to-end latency of communication and energy consumption.

In Figure 6, it is observed that D-MAC the network throughput is higher than IEEE 802.15.4 in each case. This outcome is explained by the fact that the delivery ratio is directly related to the SO value, and D-MAC performs SO adaptation based on the data traffic. While, in IEEE 802.15.4, as more source nodes are added to the network the performance is decreased because contention increases for obtaining channel that results in buffering and packet drops.

Another important factor in the performance evaluation is the size of interface queue (IFQ). The length of IFQ defines the buffering capacity at a node but greater the IFQ higher will be the delay. In figure 7, the impact of varying IFQ on average end-to-end delay is shown. While, SO is small and IFQ is large a high end-to-end latency is observed for the IEEE 802.15.4. This is because the superframe duration is not enough to carry all the packets generated by PAN members. While D-MAC has very little impact by varying the length of IFQ because of its dynamic nature.

Figure 8, shows the average energy consumption for each bit transmitted through D-MAC and IEEE 802.15.4. The energy consumption of D-MAC is lower as compared to IEEE 802.15.4. D-MAC in this scenario cannot aggressively save energy because nodes are continuously transmitting data. If nodes periodically transmit data then during idle network operation, duty cycle can be aggressively lowered to save energy.

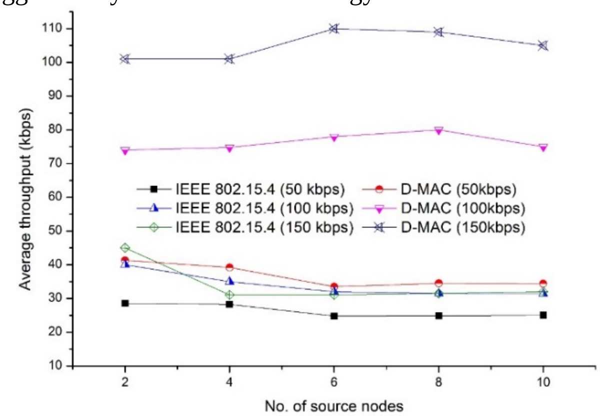

Figure. 6. Throughput of D-MAC and IEEE 802.15.4 against number of nodes

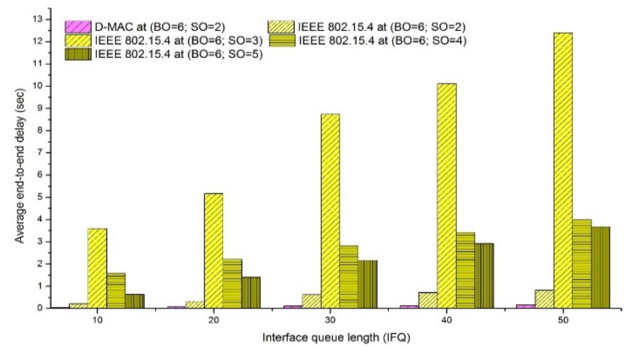

Figure. 7. IFQ length impact on average end-to-end latency of D-MAC and IEEE 802.15.4

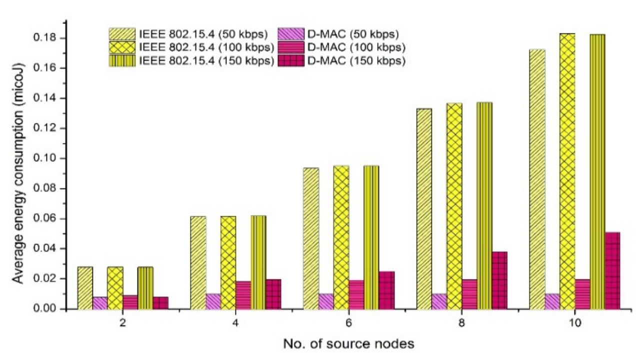

Figure. 8. Energy consumption per bit of D-MAC and IEEE 802.15.4 at (BO=6; SO=4)

5.3 D-MAC versus Existing Dynamic Duty Cycle Algorithms

Figure 9 shows the average network throughput of D-MAC, IEEE 802.15.4, DSAA [8] and DBSAA [10] at different BO. Due to fixed SO and BO the network throughput of IEEE 802.15.4 decreases with increasing BO. DSAA [8] only adjust SO whereas BI is fixed as a result at lower BO the BI is small and contention is relatively high as compared to higher BO. Therefore, it out performs IEEE 802.15.4 but is unable to match the performance of D-MAC and DBSAA that dynamically adjusts both SO and BO. D-MAC dynamically adjusts the superframe resulting in enhanced network performance.

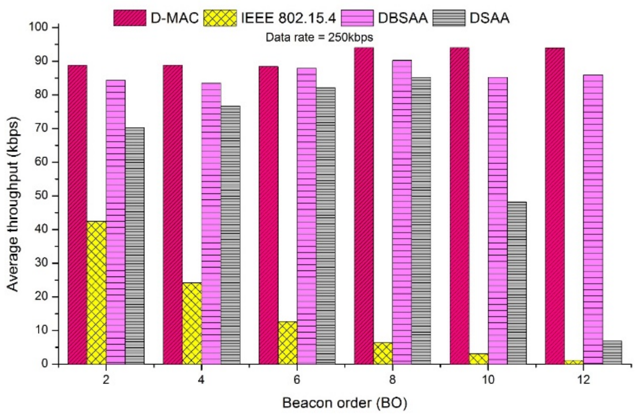

Figure. 9. Throughput of D-MAC, IEEE 802.15.4, DSAA [8] and DBSAA [10] at different BO

6. Conclusion

In this paper, we proposed an algorithm called D-MAC for WBAN, which is used to dynamically adapt the BO and SO concurrently by considering the content requirements of application. The central controller PAN coordinator computes the estimated superframe considering the WBAN network requirements. During the event reporting the duty cycle of source nodes is altered after the expiry of every BI. D-MAC shifts to the default setting when no event reporting is observed to conserve energy consumption. The overall results show that D-MAC is capable of adjusting the duty cycle of nodes dynamically and hence provides better results in terms of network throughput, energy consumption and end-to-end delay when compared to IEEE 802.15.4, DSAA [8] and DBSAA [10]. In future, the dynamic behavior of D-MAC can be further extended in cluster tree topology.

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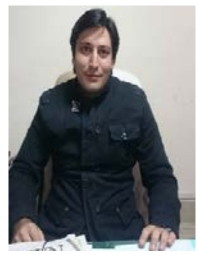

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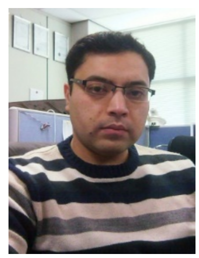

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