Optimal Beacon and Superframe Orders in WSNs

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***Abstract*— Most of Wireless Sensor Network (WSN) applications aim to utilize low data rates, consume very low energy, and operate in short range areas at low costs. IEEE 802.15.4 standard is proposed in order to achieve such needs by putting standards for physical and Medium Access Control (MAC) layers. MAC operates in either beacon enabled or beaconless modes. Performance of the standard beacon enabled mode is basically affected by beacon frame parameters, which are Beacon Order (BO) and Superframe Order (SO). These two parameters determine node's active and inactive periods, they also determine node's duty cycle. BO and SO values must be chosen carefully when the standard MAC is parameterized since some combinations may degrade standard performance dramatically. Finding the optimal (BO, SO) combination is an application-based issue since diverse WSN applications work through different arrival rates at different duty cycles. This paper investigates the standard beacon enabled mode behavior through intensive simulation and revels the optimal range of (BO, SO) combinations for specific star topology with different number of nodes. The investigated application is evaluated in terms of energy consumption, average end to end delay and throughput. Moreover, this paper proposes an adaptive algorithm that converges to the network current performance and improves network performance accordingly, irrespective of the duty cycle. The performance of the new adaptive algorithm is compared to that of the original MAC algorithm using QualNet 5.2 simulator. The new adaptive algorithm outperforms the original MAC algorithm as it reduces energy consumption up to 7%, decreases average delay by 26%, and increases throughput by 16%.**

Keywords-Wireless sensor networks; IEEE802.15.4; Beacon enabled; Superframe structure; Energy consumption.

I. INTRODUCTION

Recently, most wired sensors are replaced with wireless ones forming the emerging era of Wireless Sensor Networks (WSNs). WSNs consist of sensing devices that can communicate with each other and with the surrounding environment via wireless communication medium [1] [2]. Huge number of sensor nodes are often scattered in unreachable areas, and WSNs are often battery powered and cannot be easily recharged. Moreover, it is reasonable to force sensor nodes to track and monitor phenomena for months or even years [2].

Energy conservation is the main concern for researches in the area of WSN, these studies focus on designing WSN energy efficient algorithms and standards, one of which is the IEEE 802.15.4 [3]. IEEE 802.15.4 refers to Wireless Personal Area Network (WPAN) standard proposed by the Institute of Electrical and Electronic Engineers Task Group 4 (IEEE TG4) to support Low Rate (LR) applications; it is often referred to as LR-WPAN IEEE 802.15.4 standard. LR-WPAN is designed for home, building and industrial automated applications [4].

IEEE802.15.4 standard supports both the physical and the Media Access Control (MAC) layers. IEEE802.15.4 MAC supports two types of devices; Full Functional Devices (FFDs) and Reduced Functional Devices (RFDs). FFD acts as a regular coordinator and/or as a sink node. If both features are taken, the node typically referred to as PAN coordinator (PANc). However, RFD acts as an ordinary end device [4-6]. Both FFDs and RFDs communicate with each other forming two types of topologies: star and peer to peer topologies. Peer to peer topology can be classified to either a mesh or a cluster tree topology [6-8].

IEEE802.15.4 standard operates in three different Radio Frequency (RF) bands and it supports different data rates [4]. The 2.4 GHz RF band is widely used in IEEE802.14.4 based applications due to the following: Firstly, there is no license required to operate in this RF, and secondly, it offers the highest data rate amongst the 16 operating channels [4].

IEEE802.15.4 MAC operates either in beacon enabled or beaconless modes. In the beacon enabled mode, FFD broadcasts regular beacon frames in order to advertise itself to the other nodes The beacon frame includes information that enables the nodes to synchronise with each other when they need to access the channel [9][10]. Furthermore, beacon frame includes information that indicates whether there is some pending data for some nodes. The time between two successive beacons is referred to as the Beacon Interval (BI), which divided virtually into 16 equal sized slots. BI duration is specified by the Beacon Order parameter (BO) according to the following formula [9]:

$$BI = aBaseSuperframeDuration * 2^{BO} \quad (1)$$

Nodes can use the channel during the whole BI period or can sleep for some time portions; the parameter which decides that is the Superframe Order (SO), the SO decides the Superframe Duration (SD) active session according to the following formula [9]:

$$SD = aBaseSuperframeDuration * 2^{SO} \quad (2)$$

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

aBaseSuperframeSuration value depends on the slot duration according to the following formula:

aBaseSuperframeDuration= aBaseslotDuration * total number of slots (3)

Typically, time durations are expressed in term of a general time unit, that is, the symbol. The value of one symbol in seconds depends on the chosen RF band. However, the 2.4 Ghz RF band works in 62500 symbol/s at which one symbol brings out 16 µs, and as each slot duration (aBaseslotDuration) equals about 60 symbols, then the total 16 slots contribute in 960 aBaseSuperframeDuration symbols are equal to 15.36 ms. From those equations, node can infer the duration of its sleep period. All those concepts can be indicated through one concept which is the duty cycle (D). It is the percentage of time the node is awake from the whole time between the two successive beacons. D is mathematically expressed in (4) [9][10]:

$$D=SD/BI * 100\% \quad (4)$$

When a node need to access the medium, it has to locate the beginning of the next time slot in order to compete for the channel, thus, it follows the contention based algorithm followed by the standard, that is, the slotted Carrier Sense Multiple Access/Collision Avoidance algorithm (CSMA/CA); this is why this time portion is referred to as Contention Access Period (CAP) [9][10]. Furthermore, the standard empowers PANc with the authority to assign some slots excessively for some nodes during which they can utilize the channel alone. This is why such time slots are referred to as Guaranteed Time Slots (GTS).

The optional period which includes those slots is referred to as the Contention Free period (CFP) and it include maximum of seven GTS which are preserved optionally after the CAP period. CAP and the optional CFP together are referred to as the Active Period. Active period is the time during which nodes can be active and are able to use the medium. The duration of this period is often referred to as the SuperFrame Duration [9][10]. More precisely, every time the node needs to access the channel, it needs to locate the boundary of what is called the slotted/un-slotted CSMA backoff period. The Backoff period unit is indicated through the aUnitBackoffPeriod which equals to 20 symbols or 0.32 ms [10]. The lengths of the discussed periods are assigned through the beacon frame which is transmitted in the first time slot (slot 0) [4].

Obviously, improving the beacon enabled standard performance is directly related to the chosen BO and SO values. How to decide the optimal BO and SO values that achieve the best performance is an application related issue. For example, an application may have packets ready for transmission every second but needs to be active for 30 minutes and sleep for 30 minutes. Some applications spend most of the time inactive, thus, i.e., low duty cycles; others need to work through full duty cycles, while many of applications need to sleep for some time portions. Hence, each application has its own special case that has much to do in the decision of BO and SO values, keeping in mind that the basic building block of any network topology consists of seven nodes (piconet). Therefore, we need to find a mechanism that is general enough for beacon enabled MAC coordinator to regularly examine PAN status and performance to adapt the superframe parameters and durations.

This paper is organized as follows. Section II summarizes some of literature work which is closely related to the paper topic, while section III investigates the problem and illustrates the followed methodology. Section IV clarifies the proposed algorithm. The algorithm performance is then evaluated in Section V. Finally the whole paper topic, analysis and work are concluded in the last section along with some ideas and work proposed to be adopted in the future.

II. RELATED WORK

Since the launch of IEEE 802.15.4 standard, many researches took place that analyse the standard performance either mathematically through analysis models or virtually through simulation or both. Those researches are primarily aimed at finding ways for enhancing the standard performance especially when it comes to energy consumption. Such interests aimed at choosing the best standard parameters values that suits the applications to work for the longest time possible. f those studies is listed below.

In [11], the IEEE 802.15.4 standard performance is evaluated in terms of throughput and packet delivery ratio. The study focused in the quality of service (QoS) for real time sensor applications and provides an enhancement to the current IEEE 802.15.4 beacon enabled standard by dynamically allocating the already existed GTS. The standard performance metrics were evaluated through varying both BO and SO values while preserving the one dynamically allocated GTS. The study considered both 100% and 50% duty cycles. And, the maximum SO and BO values tested were 6 due to the association latency that may result from choosing higher values that are not suitable for WSN applications. Other QoS property examined was the collision probability which was evaluated through varying number of nodes. Simulation run through NS2 simulator and applied on a star topology. Results showed that high values of BO increase throughput due to the decreased possibility of packets drops. Moreover, results revealed that collision probability increases as the number of nodes increases which will degrade the successful use of the channel and hence achieve poor throughput.

In [12], the performance of beacon enabled IEEE 802.15.4 is evaluated in term of energy consumption in a large scale clustered tree network. Analysis of the IEEE 802.15.4 MAC were performed on a real ZigBee nodes applied on home network areas by varying BO values between 6 and 10 while fixing SO value to 0. High fraction of packets transmitted is sacrificed for the aim of minimizing the power consumption by allowing nodes to stay active for only 15.36 ms and turn the transceiver off else after. Results revealed that power consumption keeps on decreasing by increasing BO to some value (approximately 10) after which it is started to increase again. However, the study considered only very low duty cycles due to the small fraction of CAP and did not consider the effect of SO on the standard performance at all.

In [13], performance of the slotted CSMA/CA is investigated through studying the effects of SO, BO and Backoff Exponent (BE). However, the same study took place in [3], which considered other criteria such as the number of nodes and the data frame size. Simulation experiments were done for 13 different values of BO and SO which contributes in a 100% duty cycles. Those experiments intended to reach up the best range of traffic load offered that achieves the optimal performance metrics values. Metrics which were evaluated are the throughput, average delay and network reliability. The best range of offered load that achieved the optimal trade-off between throughput and average delay utility was found to be between 35% and 60%. This study did not concern parameters behaviour with sleep period enabled.

However, Shu et al. [6] proposes an optimization problem in order to achieve the minimum energy consumed under the packet delivery reliability constrain. The objective function was achieved after finding optimal values for the two decision variables which are BO and SO. Experiments run through a C implemented simulator and applied on a star topology. Simulation results revealed that for a network where packets generated under Poisson processes and where the number of nodes varies from 5 to 35, the optimal value of BO was found to be 7 while that for SO was found to be 1, that's just in case that number of nodes is less than 15 and 2. However, choosing optimal values for BO and SO depends on the quality of service constraints chosen.

The authors in [14] propose an algorithm that reconfigures only the BO parameter of the IEEE 802.15.4 superframe structure. The Beacon Order Adaptive Algorithm (BOAA) was investigated and applied on a star topology. Changing BO depends on the inter-arrival rate which reflects the frequency of communication. Adjusting the value of BO changes the length of the duty cycle due to the dynamic changing of the beacon interval. Experimental results showed that increasing the value of BO contributes in saving power due to the increased inactive period. However, this power saving improvement would be at the expense of the delay because increasing BI would cause nodes wait more time for the next beacon which determines their new configuration. Throughput was not taken under consideration because only small numbers of nodes were allowed to send a light traffic. This makes BOAA suitable only for simple applications which need no real-time or complex configuration.

In [15], IEEE 802.15.4 standard performance is investigated in terms of throughput, energy consumption and reliability by applying the standard on ideal and non-ideal star topologies. The focus was on changing nodes number while varying some of IEEE 802.15.4 standard configurations such as the availability of synchronization, BO and SO. According to the results achieved, some recommendations were suggested that aid in configuring the standard, configuring applications that follow the standard and how to improve the standard. However, such recommendations can only be taken under consideration when applying the standard on the same topologies tested where only the behaviour of BO=SO (100% duty cycle) considered . Moreover, most of the suggestions provided were based on theoretical ideas and not on practical achieved results. However, all such researches are very application specific and none gives a general enhancement that can be applied on all WSN applications.

III. METHODOLGY AND PROBLEM ANALYSIS

In order for the current transaction to complete during the current superframe active session, the remaining CAP backoff periods must be sufficient enough to accommodate the whole CSMA/CA operations; otherwise, nodes shall wait for the next superframe. If this situation continues to happen, network performance will be adversely affected. Actually, PAN performance is adversely affected by high and low values of both BO and SO parameters. This section investigates the effect of all possible (BO, SO) combination values on IEEE 802.14.4 standard performance through simulation. The Simulation study is conducted using QualNet 5.2 simulator. Simulation parameters are summarized in Table 1.

PANs consist of one FFD that is the PANc while the other devices are RFDs. RFDs transmit a 50 byte Constant Bit Rate (CBR) packet every one second through the simulation period. Standard performance is investigated in terms of energy consumption, average end to end delay and throughput. Results are categorized according to the duty cycle. In other words, those (BO, SO) combinations that achieve the same duty cycle are depicted in one figure for each performance metric. Duty cycle concept is expressed according to the following formula:

$$D = 2^{SO-BO} * 100\% \tag{5}$$

As SO value is always lower than the BO value, D can be expressed as:

$$D = 1/2^{BO-SO} * 100\% \tag{6}$$

Hence, $D \in$ {100%, 50%, 25%, 12.5%, 6.24%, 3.13%, 1.56%, 0.78%, 0.39%}.

For each duty cycle in the set, the standard performance is investigated for the seven PANs in order to study the effect of the number of nodes in one piconet, so that we can generalize the results achieved for larger network sizes as the basic building block for any network is seven nodes. However, due to space consideration, we just depict results for 100% and 50% duty cycles and which reflect energy consumption and average end to end delay behaviour.

TABLE 1. QUALNET SIMULATION PARAMETERS FOR SEVEN PAN SCENARIOS

Parameter	Value
Simulator	QualNet 5.2
Physical and MAC	IEEE 802.15.4
Area	80 m * 80 m
Number of nodes	2-8
Transmission range	10 m

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Simulation time	1000 s
Channel Frequency	2.4 GHz
Energy model	MICAZ
Antenna Height	0.08
Traffic	CBR
Payload size	50 byte
Arrival Rate	1 second
BO and SO values	1-14

A. Total Energy Consumption Results (mWh)

Fig. 1 and Fig. 2 depict total energy consumed in different PAN sizes. PANs work in the 100% and 50% duty cycles which are determined by all possible (BO, SO) beacon frames combinations sent by the PANc. We note that despite the value of SO, combinations with BO values greater than 3 increase BI value. This result in longer time between two successive beacons and thus decreases beacon overhead which contributes in conserving energy. Unfortunately, this is not always the case, since very high SO values starting from 9 increase the possibility for idle listening due to the longer time nodes spend doing nothing which will dissipate energy.

However, increasing the duty cycle by either fixing BO while increasing SO values or fixing SO while decreasing BO values, decreases sleep time portion as SO becomes closer to BO. Unfortunately, this may increase energy consumption at combinations with high SO values (starting from 9) due to the idle listening . However, increasing BO while fixing SO values or decreasing SO while fixing BO values leads to an increased BItherefore, it leads to lower duty cycles. This, on one hand, offers to nodes more time to sleep between active periods, thus helping in conserving energy while on the other hand decreases the need for frequent beacon frames transmission which consequently saves energy. Furthermore, very short CAP compared to the total overall BI will cause frequent CCA deference; hence, nodes shall try to transmit altogether at the beginning of the next superframe. This leads to bothsevere collision and packets re-transmission which consequently increases energy consumption.

It can be noticed that for the 1 s arrival rate, as the duty cycle decreases, there is not much big difference in energy consumption trend. We can say that the dominating energy consumption factor is the idle listening. Or in other words, to conserve energy in a piconet, it is necessary to let PAN to work through a reasonable CAP in a reasonable BI by setting reasonable BO and SO values keeping in mind that we need to avoid all combinations with BO greater than 8. Sleep mode somehow contributes in energy saving but not to that extent. The positive effect of sleep mode in energy consumption is much noticeable in inactive networks which work in very low arrival rates where there is infrequent packets transmission (every hour for example). Actually, for the 1 s arrival rate, inactive period length has much to do with the delay and the throughput behavior but it is not a big energy conserving factor. This will be more clarified in the following sections.

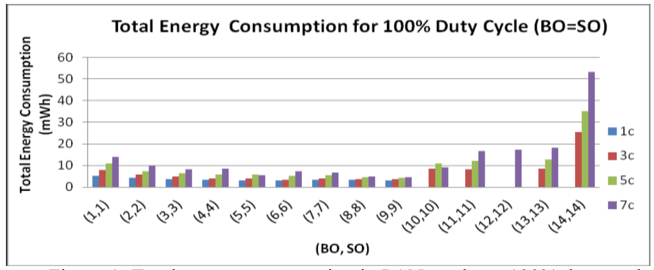

Figure 1. Total energy consumption in PAN works at 100% duty cycle

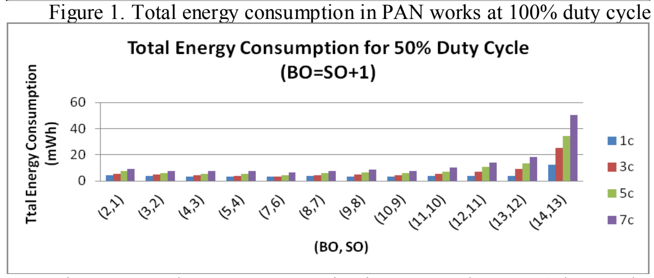

Figure 2. Total energy consumption in PAN works at 50% duty cycle

B. Average End to End Delay Results(s)

The second performance metric considered is the delay each received packet suffers during its journey from the source node to the PANc which is why it is called end to end delay. Fig. 3 and Fig. 4 depict average end-to-end delay in different PAN densities which work in 100% and 50% duty cycles determined by the whole possible (BO,SO) beacon frames combinations sent by the PANc. Results revealed that as (BO, SO) values increase, the time during which nodes may access the medium increases, and if there are more than one node want to use the medium, the average delays significantly increase because nodes will go into additional and higher backoff delays, since the backoff exponent should be higher which increases as number of nodes increases.

However, despite the value of SO, as BO increases, nodes that haven't finish their work in the current superframe shall wait until the next beacon frame initiates the active period in order to accomplish the work in the next superrframe. This case is obvious in Fig. 4 where the average delay increases dramatically if it compared to that of Fig. 3. Despite the duty cycle, all combinations with BO and SO values lower than (6, 6) contributes in very low delay (close to 0) because of the short BI which if it increases, delay increases accordingly. Unfortunately, all those combinations with BO=SO values starting from 11 results in a very long BI which on one hand delays the association process, while on the other hand may cause nodes to loose synchronization with the coordinator. Those cases result in a bad throughput as they lessen the number of the successfully transmitted packets. This explains why average delay at such combinations has values close to 0. However, at (14, 14), the first successful association occurred after 3000 s whereas the simulation period occupies 1000s; thus, no PAN activities shall take place during this time which explains the 0 delay at this combination.

In short, whatever is the duty cycle, the average delay behavior is consistent. Increasing the duty cycle on one hand decreases sleep time portion as SO becomes closer to BO. This shall decrease delay, since node shall have enough time to achieve its work during the current CAP and hence will wait less time for the next superframe in order to continue or renew transmitting its packets.

However, increasing BO while fixing SO or decreasing SO while fixing BO values leads to an increased BI and therefore leads to lower duty cycles. This offers nodes more time to sleep between active periods at the expense of completing their work in the current superframe, thus, node shall need to wait for the next CAP which definitely will increase delay as the duty cycle decreases.

In short, for 1 s arrival rate, high (BO, SO) values increase backoff delay which is proportional to the number of nodes, whereas small SO values increase the waiting delay as node shall need to wait for the next CAP to accomplish its work. Despite that the inactive period has not much effect on energy consumption, long sleep time portions will increase delay. However, this may not be the case in inactive applications which work through very low arrival rates, because in the time that low SO values decrease energy consumption dramatically, delay may increase which would obviously occur if node receives packets at the end of its active session. It can be said that for applications that work through low duty cycles, energy can be saved if delay is sacrificed.

C. Summary

For the examined CBR application that works through 1s arrival rate, it can be noticed that the closer the values of SO to BO (high duty cycles); the higher the throughput and the lower the delay and nodes percentage of collision. However, this has not much to do with energy consumption. Keeping in mind that very high values of BO on one hand will delay the association time which will adversely affect the throughput, while on the other hand will increase the delay significantly besides increasing energy due to the idle listening. Meanwhile, as number of nodes increases, collision increases, which can be noticed in short CAP, thereby, in order to decrease collision rate, CAP should be increased.

Regarding to the results achieved for the whole 9 possible duty cycles, it is revealed that for 1s arrival rate application, the Rang of combinations that is possible to achieve the optimal performance is aligned between {(6, 6) and (8, 8)}. If the standard is allowed to work in 100% duty cycle for example, its optimal performance achieved at (6, 6). However, for those applications that work in 50% duty cycle, it needs to work at (7, 6), whereas for applications that work in 25% duty cycle, it is preferred for them to work through (8, 6). Thus, if our aim is to allow the 1s arrival rate applications to work in its near optimal performance, it is preferred to allow them to work in 25%, 50% or 100% duty cycles. Unfortunately, lower duty cycles achieve bad performance in terms of the three metrics irrespective of the (BO, SO) combination, this means that unless it is necessary to follow, it is preferred to avoid such duty cycles. More generally, irrespective of the duty cycle, all those combinations with BO greater than 8 must be unconsidered when we need to implement any application that works in 1s arrival rate. Hence, (8,8) can be expressed as the cut-off value after which PAN performance drops dramatically and which may varies according the arrival rate the application may work with.

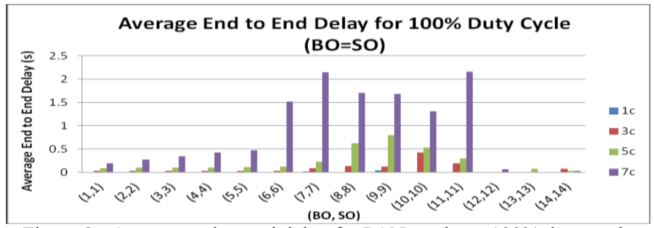

Figure 3. Average end to end delay for PAN works at 100% duty cycle.

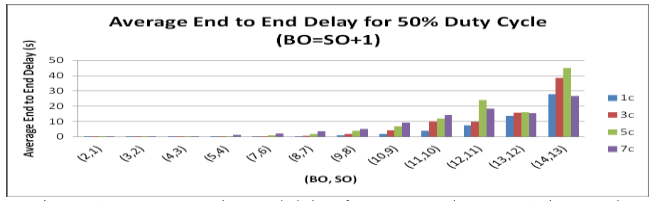

Figure 4. Average end to end delay for PAN works at 50% duty cycle

IV. PROPOSED ALGORITHM

Previous analysis indicates that in all PAN scenarios, despite that decreasing the duty cycle affects applications total energy differently, both delay and throughput behaviors are consistence, that is, as the duty cycle decreases by either fixing BO while decreasing SO or fixing SO while decreasing SO, both metrics are adversely affected. This result is two-folded; first, if we want to improve performance, we need to avoid low duty cycles by having both BO and SO values close to each other's as much as possible. In other words, we have to increase the duty cycle; this can be achieved by fixing BO while increasing SO. Moreover, enhancing delay behavior through increasing duty cycle shall improve throughput behavior accordingly. This note presents the base from where we start our new algorithm.

Following the new algorithm, PANc regularly estimates total end to end delay each node suffered so far along with the number of packets received from that node at that moment. PANc can then estimate nodes average end to end delay which will be its performance criteria according to which SO value shall dynamically change. Experiments revealed that the most reasonable number of packets after which the checking process is done by PANc is 5; hence, checking process is done every 5 packets. According to the results achieved, PANc decides if it should increase SO. In other words, if the new estimated average delay is checked to be worse than that of the previous calculated one, then PANc shall increase SO value, otherwise, do nothing. If SO increased, its value should not exceed that of BO value, and if so, it shall reset to the original SO value and restart the overall process again. This adaptive algorithm is illustrated in Fig. 5.

V. PERFORMANCE EVALUATION

The new proposed adaptive algorithm performance is evaluated along with that of the MAC original algorithm. Simulation took place on a PAN that consists of five nodes where four CBR applications are sent by the four nodes to the PANc every 1s. Recall that for 1s arrival rate application, simulation analysis investigated revealed that the (BO, SO) combination that achieves the near optimal performance in terms of the three metrics and after which the performance is adversely affected is (8, 8). Hence, our scope is limited to all possible (BO, SO) combinations which are less than and including (8, 8). Selected combinations then dynamically change according to the network performance. Other simulation parameters are identical to those presented in Table 1. Fig. 6, Fig. 7 and Fig. 8 depict performance evaluation results for the proposed algorithm compared with the original MAC algorithm in terms of the three metrics starting from average end to end delay behavior.

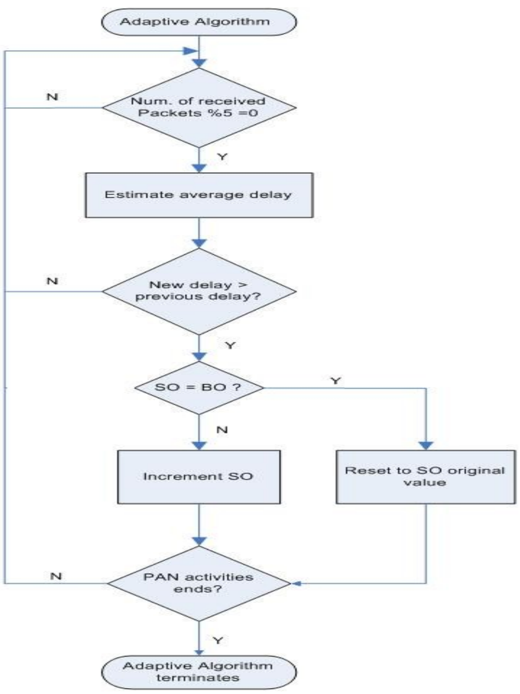

Figure 5. The new adaptive algorithm

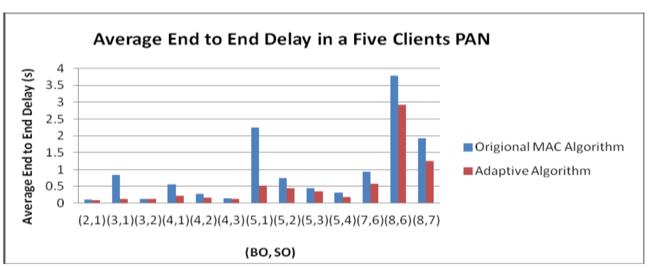

Figure 6. Average delay for the proposed and the original algorithm

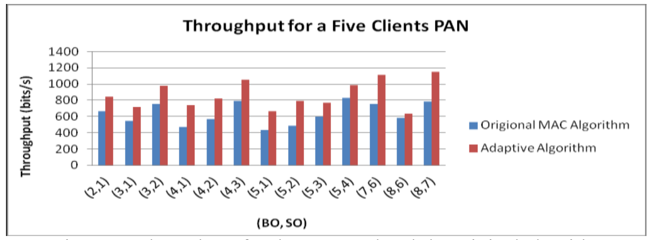

Figure 7. Throughput for the proposed and the original algorithm

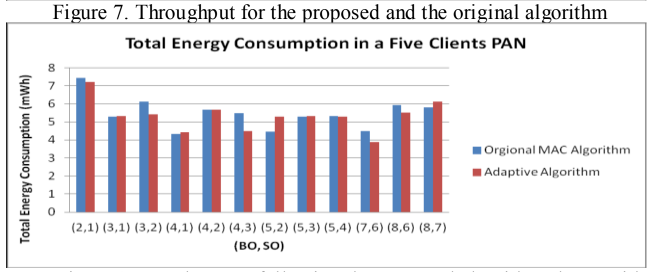

Figure 8. Total energy following the proposed algorithm along with origional algorithm

A. *Average End to End Delay (s)*

Fig. 6 depicts that the adaptive algorithm achieves less delay than the original MAC algorithm. This is simply because CAP increased gradually offering more time for nodes to accomplish their work in the current superframe, thereby, there will be less possibility for nodes to wait for the next beacon frame in order to accomplish the uncompleted work, thus, delay decreased, keeping in mind that BI remains constant as BO remains fixed.

B. *Throughput (bits/s)*

As it is expected, Fig. 7 depicts that the throughput for new adaptive algorithm outperforms that of the original one. In the adaptive algorithm, nodes have more time to perform activities and send packets in the current active session as SO increases gradually; thus, CAP increases accordingly. This gives nodes more opportunities to finish their work in the current active session which will also decrease collision rate and hence increases the throughput.

C. *Total Energy Consumption (mWh)*

It is noticed from Fig. 8 that the adaptive algorithm outperforms the original MAC algorithm at most (BO, SO) tested combinations, especially at some combinations which contribute in 50% duty cycle. At such combinations, delay is somehow moderate which will partially cause increment in SO value; thus, it allows PAN to work most of the time in 50% duty cycle; this offers to nodes more opportunities to sleep half of the period, while limiting idle listening. However, for combinations which contribute in very low duty cycles, such as (5, 2), delay is initially estimated to be very bad, hence, SO shall enhance delay accordingly, this will decrease sleep time opportunities while increasing idle listening which in turn increases energy consumption; this explains why energy consumption at such values unfortunately increases. Thereby, the proposed adaptive algorithm performance proved to outperform the original MAC algorithm in terms of average delay and throughput at all the tested (BO, SO) combinations while decreasing

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energy consumption at most of them. The new adaptive algorithm reduces energy consumption up to 7%, decreases average delay by 26% while increasing throughput by 16%.

VI. CONCLUSION AND FUTURE WORK

The chosen (BO, SO) combination has a direct impact on the performance of WSN applications that follows the IEEE802.15.4. Low SO values, compared to that of BO, serves low duty cycle applications whereas the closer SO to BO the higher the duty cycle. Thus, IEEE802.15.4 standard can support up to 9 duty cycles through just manipulating BO and SO parameters. In order to achieve optimal performance, different types of applications have to be aware of which (BO, SO) combination to use to achieve the best performance. For 1 s arrival rate application, the rang of combinations that is possible to achieve the best performance is aligned between {(6,6) and (8,8)}. The stranded can achieve its optimality if it is allowed to support 25%, 50% and 100% duty cycles applications. Lower duty cycles achieve bad performance irrespective of the (BO, SO) combination, which means that unless it is necessary to follow, it is preferred to avoid such duty cycles. (8, 8) can be expressed as the cut-off combination because other combinations with higher BOs drop the PAN performance dramatically.

The experimental work conducted for the 1 s arrival rate application revealed that improving some metrics performance may be scarified in order to allow others achieved. However, our goal is to achieve high PAN performance in term of all metrics and most importantly the power consumption irrespective of the duty cycle or the arrival rate. The proposed adaptive algorithm proved to improve the standard in terms of the average delay and the throughput at all tested (BO, SO) combinations while decreasing energy consumption at most of them. The new adaptive algorithm reduces energy consumption up to 7%, decreases average delay by 26% while increasing throughput by 16%.

As a future work, increasing the duty cycle will be achieved through following different techniques which manipulates BO values. The same work that is conducted for 1s arrival rate applications, will be investigated for other higher and lower arrival rate applicants in order to decide both the optimal and the cut-off (BO, SO) values. Then the new adaptive algorithm behavior is going to be evaluated for such arrival rates applications. Other than average end to end delay criteria, PANc shall check PAN performance according to energy consumption metric and according to which the new adaptive algorithm shall be controlled.

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