IEEE802.15.4 Performance in Various WSNs Applications

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***Abstract*— IEEE802.15.4 is a standard proposed to support physical and MAC layers for low data rate Wireless Sensor Network (WSN) applications. It provides features that allow diverse WSN applications to work at reduced energy consumption in low cost. These applications can be classified according to the arrival rate of the surrounding phenomena and according to the duty cycle. This paper investigates three WSN applications with different arrival rates and different duty cycles (100% and 50%). This paper performs intensive simulation analysis on seven network scenarios with different number of nodes. The scenarios are evaluated in terms of energy consumption, average end-to-end delay and throughput. The obtained results reveal that, irrespective of application type, both average delay and throughput behaviors vary directly, whereas energy consumption varies inversely. Results also revealed that as the duty cycle increases, both average delay and throughput improve. Improving one of the two metrics, by just increasing the duty cycle, assures enhancing the other metric, accordingly.**

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

I. Introduction

Wired sensors are replaced with wireless ones to form Wireless Sensor Networks (WSNs). A WSN is a collection of sensing devices that communicate with each other and with the surrounding environment via wireless links [1][2]. The main source of power for the sensors is batteries. Due to the limited nature of batteries, it is essential to design sensor nodes to operate for months or even years [2]. Energy conservation is the main interest of literature studies in WSNs, which focus on designing WSN energy efficient algorithms and standards, one of which is the IEEE802.15.4 standard [3].

IEEE802.15.4 standard supports both physical and Media Access Control (MAC) layers. IEEE802.15.4 MAC supports two types of devices; Full Functional Devices (FFDs) and Reduced Functional Device (RFDs) which differ in their capabilities. FFDs can act as a coordinator or as a sink node and is typically referred to as PAN coordinator (PANc). On the other hand, RFD acts only as an ordinary end device [4-6]. Nodes with different types that follow the standard can communicate with each other's forming two types of topologies: star and peer to peer. Peer to peer topology can be classified as either a mesh or a cluster tree topology [6-8].

IEEE802.15.4 standard supports three different Radio Frequency (RF) bands [4]. The most popular RF band is the unlicensed 2.4 GHz. This band offers high data and it consumes less power [4]. IEEE802.15.4 MAC operates either in beacon enabled or beaconless modes. In beacon enabled mode, FFD devices broadcasts beacon frame regularly in order to identify itself so that other nodes can recognize their master and start associating with it. Beacon frame includes information that enables nodes synchronize with each other when they need to access the channel [9][10]. Furthermore, beacon frame includes information that indicates whether there is any pending data for nodes. As coordinator sends a beacon frame and follows it by another one, the time between those two frames is referred to as the Beacon Interval (BI) and it is divided virtually into 16 equal sized slots. BI duration can be specified through Beacon Order parameter (BO) according to the following formula [9]:

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

Nodes can use the channel during the whole BI period or can sleep for some time. The parameter used to specify this time is the Superframe Order (SO) according to the following formula [9]:

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

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

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

$$aBaseSuperframeDuration = aBaseslotDuration * total\ number\ of\ slots \qquad (3)$$

Typically, time durations are expressed in terms of general time unit that is a symbol. The value of one symbol in seconds depends on the chosen RF band. In the 2.4 Ghz RF band, a symbol equals to 15.36 ms. These concepts can be summarized through one general concept namely, the duty cycle (D). It is the percentage of time the node is awake in the BI, and mathematically is expressed as follows [9][10]:

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

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When a node needs to access the medium, it has to locate the beginning of the next time slot 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 time portion is referred to as Contention Access Period (CAP) [9][10]. Furthermore, the standard empowers the PANc with the authority to assign some slots excessively for some nodes during which they can utilize the channel alone. These time slots are referred to as Guaranteed Time Slots (GTS). The optional period, which includes those slots, is referred as Contention Free period (CFP) and can include maximum of seven GTS. CAP and the optional CFP together are referred to as the Active Period, and its duration often referred to as SuperFrame Duration (SD) [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. Thus, the standard deals with time in terms of backoff period unit which in beacon enabled mode is aligned between the slot boundaries and indicated through aUnitBackoffPeriod which equals to 20 symbols or 0.32 ms [10]. The length of each period discussed previously is assigned through beacon frame which is transmitted in the first time slot (slot 0) [4].

Improving the beacon enabled standard performance is directly related to the chosen BO and SO values. These parameters need to be chosen carefully to fully utilize the scarce resources of WSNs. How to decide the optimal BO and SO values that achieve the best performance is an application related issue. WSN applications are diverse and can be classified according to the percentage of duty cycle they work through as well as their packets arrival rate. For example, an application may have packets ready for transmission every second but need to be active for 30 minutes, and hence, shall sleep for the other 30 minutes in an hour. Some applications may work through low arrival rate such as 0.1 second, thus, can be classified as very active applications. Other applications may work through high arrival rates such as 2 seconds and classified as inactive applications, while many applications wok at low constant arrival rate which may increase suddenly according to some criteria. Hence, each application has its own special case that has much to do in the decision of BO and SO, keeping in mind that the optimal building block of any network topology consists of seven nodes (piconet).

Simulation analysis conducted in [11] focus on understanding the behavior of beacon enabled PAN according to all (BO, SO) possible combinations. However, results achieved consider one type of application with 1 second arrival rate. Moreover, results indicate that it may be impossible to achieve high PAN performance in term of all metrics. Hence, to generalize this analysis, we need to study different arrival rates for different duty cycles to improve the standard performance in terms of the three metrics irrespective of application type, which is the main goal of this paper.

This paper is organized as follows. Section II summarizes some of the literature work which is closely related to the paper topic, while Section III illustrates the followed methodology, whereas Section IV clarifies and discusses the simulation results achieved. Section V concludes the paper and offers some ideas for future work.

II. RELATED WORK

Several studies were conducted to analyse the performance of the IEEE802.15.4 standard to improve energy consumption. Many researches were proposed to tune the standard parameters to achieve the best performance of the network.

Salayma et al. [11] investigates the standard beacon enabled mode behaviour through intensive simulation applied on seven PAN scenarios. It categorizes different WSN application according to duty cycle. It finds out the optimal range of (BO, SO) combinations for 1s arrival rate applications in terms of energy consumption, average end-to-end delay and throughput. Moreover, it proposes an adaptive algorithm that outperforms the original MAC irrespective of the duty cycle. The proposed adaptive algorithm converges to the network current performance and improves network performance accordingly. However, such a work considers only Constant Bit Rate (CBR) applications with 1 second interval and results revealed may not reflect other WSN applications behavior.

Neugebauer et al. [12] proposes an algorithm that reconfigures only the BO parameter of the IEEE 802.15.4 superframe structure. The Beacon Order Adaptive Algorithm (BOAA) considers 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 as a result of the dynamic changing of the beacon interval. Experimental results show that increasing the value of BO contributes to saving power [12]. However, this power saving improvement is at the expense of sharp increase in the delay, because increasing BO would cause nodes to wait for more time for the next beacon. Throughput was not taken into consideration. This makes BOAA suitable only for simple applications.

Shu et al. [6] proposes an optimization scheme, in order to achieve the minimum energy consumption under the packet delivery reliability constraints. The objective function was achieved after finding the optimal values for the two decision variables: BO and SO. The obtained results in [6] show that, for a network with number of nodes varies from 5 to 35, the optimal BO value is 7. On the other hand, for a network with number of nodes is less than 15, the optimal SO value is 1. And for the other cases, the optimal SO value is 2. However, choosing optimal values for BO and SO depends much on the chosen quality of service constraints.

In [13], the performance of the slotted CSMA/CA is investigated by studying the effects of SO, BO and Backoff Exponent (BE). However, similar study is conducted in [3] with different criteria, such as, number of nodes and data

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frame size. Simulation experiments were conducted for 13 different values of BO and SO, all with a duty cycle of 100%. The best range of offered load that achieves the optimal trade-off between throughput and average delay utility was found to be between 35% and 60%. This study does not study the network with sleep period enabled.

In [14], the IEEE 802.15.4 standard performance is evaluated in terms of throughput and packet delivery ratio. The study focuses on 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, while preserving the dynamically allocated one GTS. However, the study considers the SO and BO values up to 6, due to association latency that may result from choosing higher values which is not sufficient for WSN applications.

In [15], the performance of beacon enabled mode 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 real Zigbee nodes applied on home network areas by varying BO values between 6 and 10, while fixing SO value to 0. Results reveal that power consumption decreases by increasing BO to some value (approximately 10) after which it increases. However, the study considers only very low duty cycles, due to the small fraction of CAP and does not consider the effect of SO on the standard performance at all.

In [16], 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 study focuses is on changing number of nodes, while varying some of IEEE 802.15.4 standard configurations, such as, the availability of synchronization, BO and SO. According to the achieved results, 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 considered when applying the standard on the same tested topologies.

III. METHODOLGY AND PROBLEM ANALYSIS

Simulation work conducted by Salayma et al. [11] discusses the standard behavior in terms of total energy consumption, average end-to-end delay and throughput for seven PAN scenarios with different number of nodes. The work in [11] considers one type of applications, and the obtained results may not reflect other applications behavior. Moreover, results indicate that it may be impossible to achieve high PAN performance in term of all metrics. In other words, enhancing some metrics performance may be sacrificed in order to improve other metrics. Therefore, to generalize our analysis, our methodology considers other WSN CBR applications. It investigates active applications which receive packets very frequently, as well as, inactive applications that work through relatively low arrival rates. This paper examines different applications; as it studies the beacon enabled mode behavior which works through different arrival rates at different duty cycles.

Hence, as a first step, we need to examine what would happen as BO and SO increase or decrease by 1 in order to realize why, how much and which metric performance is needed to be enhanced adaptively. Increasing and decreasing BO and SO by 1, means that network shall operate through 50% and 100% duty cycles. WSNs applications performance is analyzed in terms of the three metrics: total energy consumption, average end-to-end delay and throughput. Applications differ in packets arrival rate which are 0.1s, 1s and 2s. A previously specified (BO, SO) combination is allowed to change dynamically at a specified time for each application in order to study the effect of increasing or decreasing of BO or SO or both by 1.

We will study the effect of choosing the same optimal combinations achieved for 1s arrival rate application on the other two applications. According to analysis results achieved in [11], it is revealed that (7, 7) is one of the combinations that relatively achieve good performance for the 1s arrival rate application, it is chosen as a reference point to analyze the other two applications behavior. Hence, after 500s, four scenarios are examined, which are increasing or decreasing either BO=7 or SO=7 by 1 resulting in 50% duty cycle and increasing or decreasing both BO=SO by 1 achieving a 100% duty cycle. Those scenarios examined for the three arrival rates applications applied on seven PANs which differ in number of nodes and each experiment are conducted five times. Network simulation parameters are presented in Table I.

TABLE I. QUALNET SIMULATION PARAMETERS FOR SEVEN PAN SCENARIOS

Parameter	Value
Physical and MAC model	IEEE 802.15.4
Area	80 m * 80 m
Number of nodes	2-8
Transmission range	10 m
Simulation time	1000 s
Channel Frequency	2.4 GHz
Data rate	250 kbps
Energy model	MICAZ
Antenna Height	0.08
Traffic	CBR
Payload size	50 byte
Arrival Rate	0.1,1, 2 seconds
BO and SO values	(6,6) to (8,8)

IV. SIMULATION RESULTS

The following subsections discuss the results obtained for each performance metric. We depict the results for four PAN scenarios due to space consideration.

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A. Total Energy Consumption (mWh)

Four factors contribute in energy consumption and all need to be considered in investigating total energy consumption behaviour. Those contributors are the total energy a node consumes in packets transmission and reception, and the energy it dissipates during its idle listening and its sleep mode. Figures 1 to 4 depict energy consumption behavior for the four scenarios starting from one client up to seven clients.

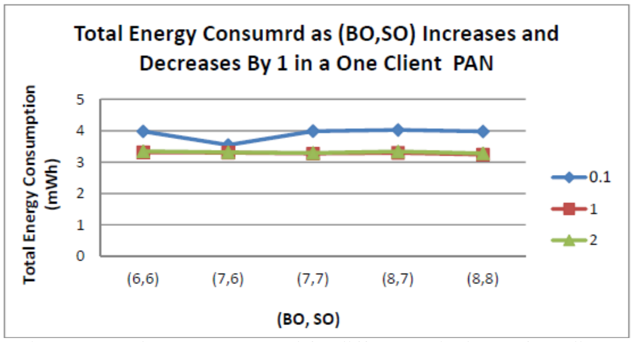

Figure 1. Total energy consumed for different arrival rates for 1client.

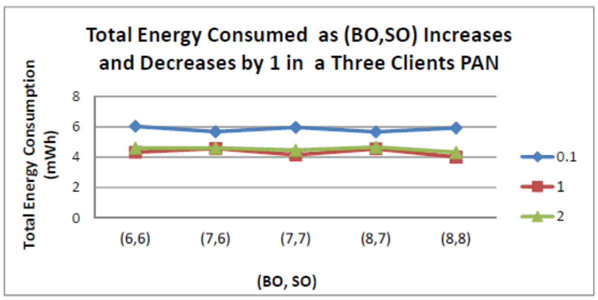

Figure 2. Total energy consumed for different arrival rates for 3 clients.

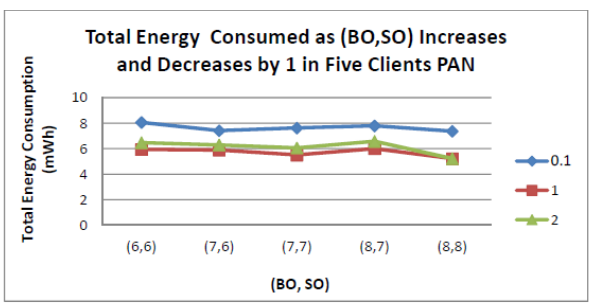

Figure 3. Total energy consumed for different arrival rates for 5 clients.

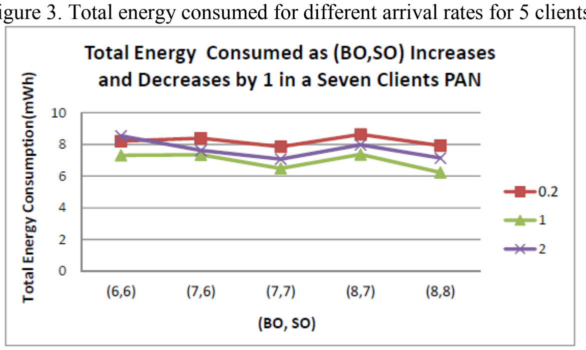

Figure 4. Total energy consumed for different arrival rates for 7 clients.

Very high arrival rate means frequent transmissions; hence, the dominating factor in energy consumption is the transmission power. However, after 500s, if the coordinator decides to increase or decrease either BO, or SO by 1, then, the node has a chance to rest and sleep for half of the BI period; thus, node saves energy. On the other hand, in low arrival rates applications, there would be more of a chance for free time while node is idle, which results in idle listening, hence, the dominating power consumption factor is idle listening. However, after 500s, if the coordinator decides to increase or decrease either BO, or SO by 1, then, node shall sleep for half of the BI period, and defer the transmission process for the next CAP if it receives a packet at the end of CAP. As the number of nodes increases, all the transmitting nodes may collide, which will cause retransmissions and as a result, energy consumption will increase. The obtained results show that for all arrival rates, increasing both BO and SO by 1 after 500s decreases energy consumption in comparison to the case of decreasing both BO and SO; this is because BI becomes longer, which in its turn, decreases beacon overhead at PANc.

B. Average End-to-End Delay (s)

Figures 5 to 8 depict average end-to-end delay behavior for the four scenarios starting from one client up to seven clients.

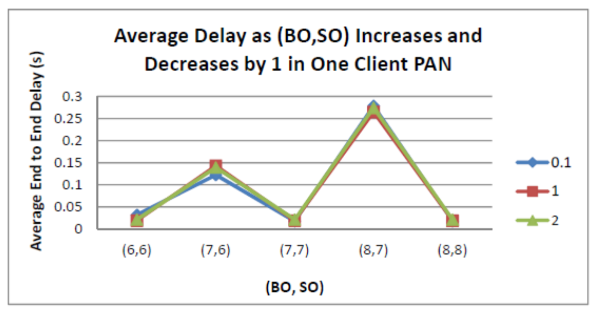

Figure 5. Average end-to-end delay for different arrival rates for 1 client.

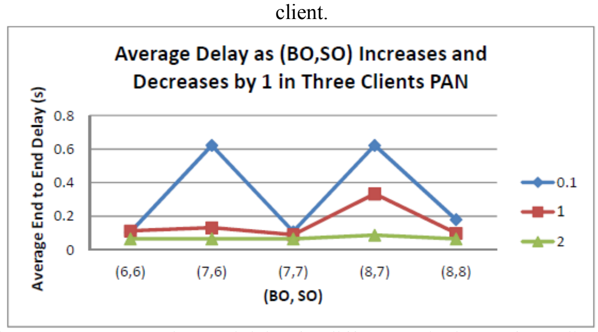

Figure 6. Average end-to-end delay for different arrival rates for 3 clients.

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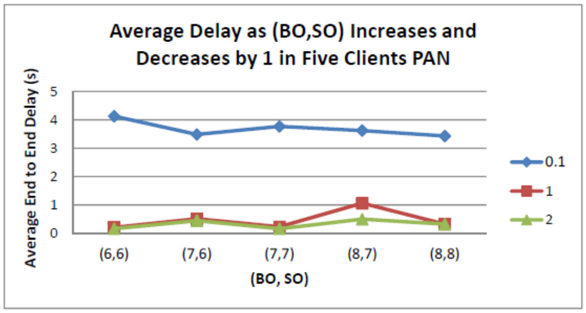

Figure 7. Average end-to-end delay for different arrival rates for 5 clients

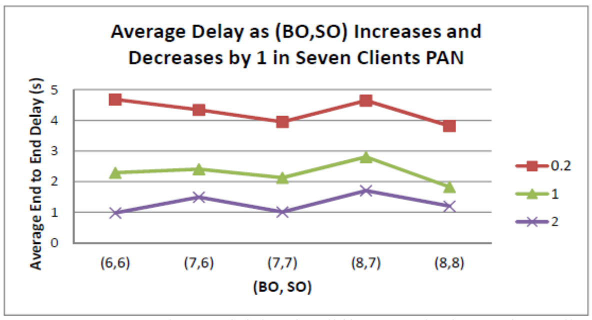

Figure 8. Average end-to-end delay for different arrival rates for 7 clients.

Despite the arrival rate, after 500s, if either BO or SO values decrease by 1, then, the duty cycle decreases to half, which cause nodes that have no time to complete their work in the current CAP, to wait for the next active period. This gets worse in active networks. As arrival rate increases, delay is less affected if the duty cycle decreases. However, if both BO and SO values are increased or decreased by 1, this achieves a full percent duty cycle, which means that nodes have more opportunity to use the medium, and this will produce the second delay factor, that is, the backoff delay. Backoff delay increases as the number of nodes increases. As the number of nodes increases, the possibility of collision increases, especially in short duty cycles, and hence, throughput decreases. This can be noticed at very low arrival rate values, such as 0.1 s. This explains why in PANs with 5 and 7 clients, delay decreases for the 0.1 s arrival rate application; it is simply because the number of the successfully arrived packets at the coordinator in a second decreases dramatically in active networks

C. *Throughput (bit/s)*

Figures 9 to 12 depict throughputs' results for the four scenarios starting from one client up to seven clients.

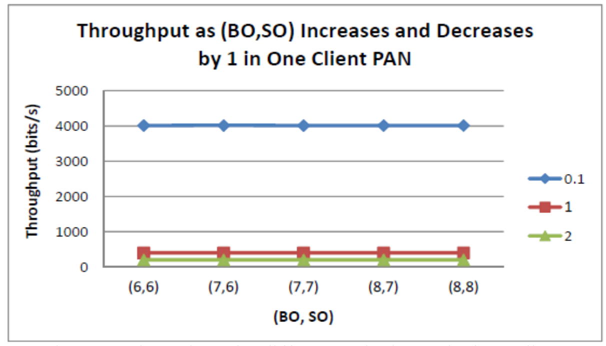

Figure 9. Throughput for different arrival rates in for 1 client.

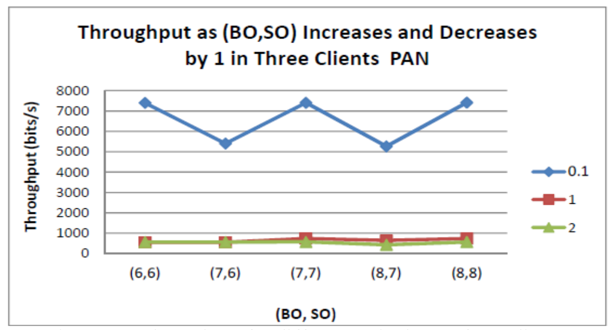

Figure 10. Throughput for different arrival rates for 3 clients.

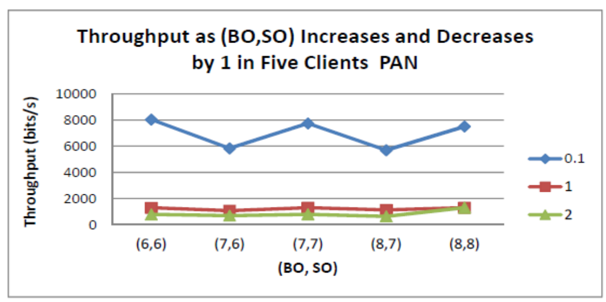

Figure 11. Throughput for different arrival rates for 5 clients.

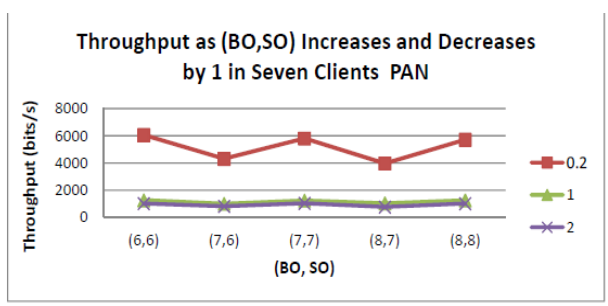

Figure 12. Throughput for different arrival rates for 7 clients.

Increasing or decreasing either BO or SO by 1, lessens the duty cycle, which cause nodes to wait for the next CAP

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in order to accomplish the uncompleted transmissions. This causes severe collision at the beginning of the next superframe structure, which increases as the number of nodes increases. Obviously, such situation adversely affects throughput. This case is obvious in very active networks that follows o.1s arrival rate. It is simply because more packets will be lost.

Increasing both BO and SO by 1 offers nodes longer CAP. This increases throughput, which is noticed as the number of nodes increases. As the duty cycle decreases, both delay and throughput are badly affected. This result is two folded: first, if we want to improve the performance, we need to avoid low duty cycles by having both BO and SO values close to each others as much as possible. In other words, we have to increase the duty cycle. Second, enhancing delay behavior through increasing the duty cycle, shall improve throughput behavior accordingly. This means that, we can propose an algorithm that enhances throughput just by enhancing delay or vice versa, this can be achieved by increasing the duty cycle.

V. CONCLUSION AND FUTURE WORK

WSN applications are diverse and can be classified according to the percentage of the duty cycle they work through and according to their packets arrival rate. Most of WSN applications follow IEEE802.15.4 standard. Performance of any WSN application is basically affected by the chosen (BO, SO) combination, thus, in order to achieve optimal performance, different types of WSN applications have to be aware of which (BO, SO) combination to activate. Decreasing the duty cycle is beneficial for active networks as the sleep periods offer the nodes the opportunity to rest; this is obvious in WSNs applications that follow 0.1 s. However, despite that decreasing duty cycle affects applications total energy differently, both delay and throughput behaviors are consistent for all arrival rates. In other words, as the duty cycle decreases by fixing BO while decreasing SO or vice versa, both metrics are adversely affected. As a future work, we suggest to design a general algorithm that adaptively improves the three metrics as the duty cycle increases irrespective of application arrival rate. Moreover, we need to investigate low and high arrival rates WSNs applications behavior in order to select both the optimal and the cut-off (BO, SO) combinations for each application. Such results are needed to develop an adaptive and general algorithm that adjust the (BO, SO) combination in accordance with the changes in the arrival rate.

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