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A Survey of IEEE 802.15.4 Effective System Parameters for Wireless Body Sensor Networks

A. Moravejosharieh*and J. Lloret

Department of Computer Science and Software Engineering, University of Canterbury, New Zealand & Instituto de Investigacion para la Gestion Integrada de zonas Costeras, Universidad Politecnica de Valencia, Spain

SUMMARY

Wireless Body Sensor Networks (WBSNs) are offered to meet the requirements of a diverse set of applications such as health-related and well-being applications. For instance, they are deployed to measure, fetch and collect human body vital signs. Such information could be further used for diagnosis and monitoring of medical conditions. IEEE 802.15.4 is arguably considered as a well designed standard protocol to address the need for low-rate, low-power and low-cost WBSNs. Apart from the vast deployment of this technology, there are still some challenges and issues related to the performance of the Medium Access Control (MAC) protocol of this standard which are required to be addressed. This paper comprises two main parts. In the first part, the survey has provided a thorough assessment of IEEE 802.15.4 MAC protocol performance where its functionality is evaluated considering a range of effective system parameters i.e. Some of the MAC and application parameters and the impact of mutual interference. The second part of this paper is about conducting a simulation study to determine the influence of varying values of the system parameters on IEEE 802.15.4 performance gains. More specifically, we explore the dependability-level of IEEE 802.5.4 performance gains on a candidate set of system parameters. Finally, this paper highlights the tangible needs to conduct more investigations on particular aspect(s) of IEEE 802.15.4 MAC protocol. Copyright © 2015 John Wiley & Sons, Ltd.

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KEY WORDS: WSN; WBSN; Internal Interference; System Parameters; performance evaluation; IEEE 802.15.4

1. INTRODUCTION

Advances in microelectronic devices such as tiny microprocessors and low-power radio technologies have provided the opportunity of creating low-cost, low-power and multifunctional sensor devices. Such sensors are used to observe the surrounding environment, collect certain information and take proper actions on it. Wireless Sensor Network (WSN) using IEEE 802.15.4 standard is expected to play a key role in a diverse set of applications, e.g. medical field [1, 2, 3], agriculture, environment monitoring, security purposes (intrusion detection), military, motion detection [4], sports [5, 6] and entertainments. For example, in the medical field, a WSN attached to a body (WBSN) to collect the vital signs can remotely monitor the medical condition of a patient such as blood pressure, heartbeat or even blood sugar. Thereafter, it is possible to report the gathered information to the professionals either periodically or on event-detection basis [7, 8, 9, 10, 11, 12].

The IEEE 802.15.4 standard [13] is one of the mature and well-established protocols being standardised for low-power and low-cost Wireless Personal Area Networks (WPANs). Wireless

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*Correspondence to: A. Moravejosharieh, Department of Computer Science and Software Engineering, University of Canterbury, New Zealand
E-mail: amir.moravejosharieh@pg.canterbury.ac.nz

sensor network is considered as a type of WPAN, and its standard protocol supports both Medium Access Layer (MAC) and the Physical Layer (PHY). In the PHY layer, arguably the most popular frequency band is the 2.4 GHz band. There are two types of interference in this frequency band: *internal* interference which is the mutual interference of WBSNs over each other and *external* interference which is caused by other technologies e.g. WiFi or Bluetooth over WSNs [14, 15]. The impact of external interference on the performance gain of IEEE 802.15.4-based WSNs has been extensively investigated and the effective MAC protocol modifications are proposed accordingly [16]. Therefore, the literature related to the external interference is beyond the scope of this article. In this survey, we focus on the impact of internal interference on the performance of IEEE 802.15.4 MAC protocol. At first we provide a critical review indicating the influences of the several system parameters (i.e. MAC and Application layer parameters) on the performance gain of the WSNs [17]. Secondly, we investigate a number of approaches that are proposed to improve the functionality of the MAC layer in IEEE 802.15.4-based WSNs [18, 19] in presence of internal interference. Thirdly, we have conducted a preliminary simulation experiment to show the influence of a set of MAC parameters on the IEEE 802.15.4 MAC functionality in the presence of intensifying internal interference.

In this survey, we are interested in Wireless Body Sensor Networks (WBSNs) that are used in medical applications. This is due to being subjected to the high level of reliability and timeliness when they are deployed in the medical applications. Although the wireless body sensor network (WBSN) has many characteristics in common with the classic WSN (same MAC and PYH layers functionalities), the key differences are their relatively small size (both in number of sensors and the network diameter) and the mobility feature of networks as a whole. The IEEE 802.15.4 standard protocol is expected to remain a key protocol for body sensor networks applications for a considerable amount of time in future [20]. This is due to availability of cheap and mature components that are compatible with this standard and are already being deployed in health-related applications. Therefore in our simulation experiment, we considered a situation where a large number of people wearing WBSNs are co-located at the very close vicinity, as can happen for example in sport events. Clearly, this makes WBSNs to compete to gain access to the operating frequency. In such scenarios, as the number of WBSNs (people) becomes larger, the probability of achieving the desired reliability and timeliness becomes significantly lower. More specifically, we have selected a set of parameters and defined a maximum and minimum values for each and every parameter in the set in order to determine the influence of the possible combinations of these values on WBSN's performance gain in the presence of intensifying internal interference.

In this survey, we answer the following questions: What are the effective system parameters on WBSN performance gains? What were the performance measures and evaluation tools employed by researchers to carry out their studies? How destructive is the impact of the internal interference on WBSN performance gains? Finally, what are the proposed solutions to mitigate the impact of internal interference according to the existing state of art? We believe that it would be highly beneficial to provide a survey in which the performance of the IEEE 802.15.4-based WBSN is evaluated from the aspect of effective system parameters. Furthermore, conducting a simulation-based study on the effective system parameters in the presence of intensifying internal interference can be persuasive for research communities to carry out further related investigations.

This paper is organised as follows: Section 2 provides the necessary background information about the IEEE 802.15.4 physical layer, MAC layer and the MAC layer functionality. The first part of section 3 is related to the state of art regarding the impacts of various system parameters on the WSN/WBSN's performance gain, and in the second part, the proposed approaches to enhance the IEEE 802.15.4 MAC protocol are elaborated. Section 4 presents the conducted simulation study and the explanation of the performance measures. The results of our simulation-based study are discussed in detail in section 5. Finally, this survey is concluded in section 6. The last section also highlights the need for more comprehensive research on particular challenges and issues in the field of WBSNs.

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2. BACKGROUND

In this section the essential descriptions of both PYH and MAC layers are provided followed by the explanation of the IEEE 802.15.4 standard functionalities [13].

2.1. Physical layer

In the IEEE 802.15.4 standard, different physical layers are supported in 2.4 GHz band. Arguably the most widespread and commonly-used band is the O-QPSK PHY. In this paper, we are going to focus on this band simply due to the availability and the accessibility of the popular ChipCon CC2420 transceiver that is compliant to this band. The data rate in this band is 250 kb/s. The 2.4 GHz band is further subdivided into 16 non-overlapping channels. Each channel is 2 MHz wide and the centres of two adjacent channels are separated by 5 MHz. In order to study the impact of internal interference, we only consider the interference caused by neighbouring WBSNs and the interference caused by two adjacent channels is disregarded [21].

2.2. MAC Layer: Beaconed Mode

The PAN coordinator, or for more simplicity the coordinator starts the network and set the essential operational parameters such as the duty cycle, the frequency band. The sensor devices (hereafter called sensors) initially associate themselves with the coordinator and any data exchange occurs thereafter. In this standard, there are two operating modes: *beacon-enabled* mode and *non-beacon* mode. In beacon-enabled mode the time is compartmented by beacons packets and each compartment is called a *superframe*. Figure 1 depicts the beacon-enabled mode of a superframe structure.

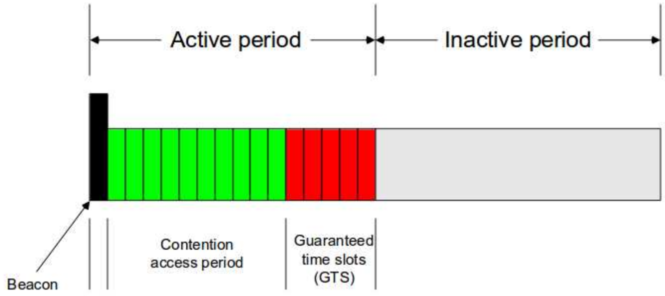

Figure 1. Superframe structure of IEEE 802.15.4 beaconed mode

Each superframe is further subdivided into an active and an inactive period. The active period contains 16 equal sections called *time slots*. In the very first time slot, the coordinator transmits a beacon packet containing all the necessary settings for the network functioning. The beacon packet transmission occurs without using carrier-sensing. Immediately after sending beacon packet the *Contention Active Period* (CAP) starts. During the CAP, sensors attempt to transmit the uplink packets to the coordinator or request the pending downlink packets using a medium access method called Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). Some of these slots at the end of a CAP can be considered as a *Guaranteed Time Slots* (GTS) and can be allocated to particular nodes for either uplink or downlink transmissions. Transmissions in GTS occur without using the CSMA/CA method. Sensors receive beacons to maintain the synchronisations with the coordinator, use the CSMA/CA method to transmit the collected data to the coordinator or sleep otherwise. The coordinator has to be switched on for the entire CAP duration, whereas in the inactive period both coordinator and sensors sleep to save up their energy.

The length of the superframe and the relative length of the active period within a superframe are configurable. The duration of a time between two consecutive beacon packets is called “Beacon

Interval" (BI) and is determined as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO} \tag{1}$$

where the configurable parameter BO ("beacon order") is an integer between 0 and 14, and $aBaseSuperframeDuration = 15.36$ ms for the 2.4 GHz O-QPSK PHY. The length of the active period is called superframe duration (SD) and is given by

$$SD = aBaseSuperframeDuration \times 2^{SO} \tag{2}$$

for $0 \leq SO \leq BO \leq 14$. The parameter SO is configurable and is called the "superframe order".

2.3. MAC Layer: Network Start and Synchronization

The coordinator as the Body Sensor Network (BSN) starter, can initially scan all the available channels using passive or active MAC layer scan. The collected results can further be used by the higher layers to determine the operating frequency, duty cycle settings and PAN identifier. Thereafter, the coordinator periodically broadcasts the beacon packets. Once the beacon packets are transmitted, the sensors are able to discover their coordinators performing active or passive channel scan (refer to standard draft [13] subsection 5.1.2.1.2). To accomplish this, the sensors scan all channels and listen to each channel for a pre-determined duration to detect their coordinator's PAN identifier. It is assumed that the sensors know about the beacon order and they stay in each channel for the period of a beacon interval before proceeding to scan the next channel. This assumption is considered to avoid the coordinator discovery procedure which is a time-consuming process [22, 23]. After discovering the coordinator, sensors attempt to associate with their coordinators via sending the association request packets during the CAP (refer to standard draft [13] subsection 5.1.3.1).

Beacon packets are transmitted periodically to maintain the associated sensors synchronised with the coordinator (refer to standard draft [13] subsection 5.1.4.1). For example a beacon packet generally may contain information such as announcing the pending download traffic for particular sensors, or allocation of GTS to some sensors. We assume that once a sensor discovered the first beacon packet, it maintains its synchronisation with that coordinator and attempts to receive the future beacon packets. As mentioned earlier, the beacon packet is transmitted periodically and the period (depending on the value of the BO parameter) is determined using equation 1. For instance, BO = 6 corresponds to BI = 0.98304 seconds which means that the beacon packet is going to be transmitted every 0.98304 seconds. Generally, when a sensor does not receive four consecutive beacon packets, it concludes that the synchronisation with its associated coordinator has been lost and informs its higher layers, which then start the searching and association process again. The sensor that has lost its synchronisation is called an *orphan* sensor. The orphan sensor attempts to re-discover its correspondent coordinator and meanwhile it cannot transmit or receive any data (refer to standard draft [13] subsection 5.1.2.1.3). The data packets generated during the orphan time are buffered in the MAC layer and will be discarded and count as lost packet once the buffer becomes full.

3. RELATED WORKS

The related literature is reviewed in this section. The impact of various system parameters on WSN/WBSN's performance gain are discussed in the following subsection. The proposed approaches and probable solutions to mitigate the negative impacts of internal interference on WSN/WBSN performance gains are explained thereafter.

3.1. Effective System Parameters

According to the beacon-enabled mode of IEEE 802.15.4, sensor nodes compete with each other to gain access to the medium. CSMA/CA is the most commonly used strategy in IEEE 802.5.4

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(see section 5.1.1.4 in [13]). This enables sensor nodes to make sure the channel is not currently utilised by other sensor nodes. CSMA/CA strategy has its own internal parameters such as Beacon Exponent (BE), macMinBE and macMaxBE. The following literature explains the importance of CSMA/CA internal parameters (mainly macMinBE and macMaxBE). Many investigations are conducted to study the impact of CSMA/CA internal parameters on WSN/WBSN performance. Koubaa et al. presented the performance of CSMA/CA algorithm of IEEE 802.15.4 while the beacon-enabled mode is deployed [24]. In their study, the performance of slotted CSMA/CA is investigated for the configuration of different network parameters. More particularly, the impact of BO, SO and BE on the network performance (throughput, average delay and probability of success) were studied. The results show significant increase on network throughput as the offered traffic load (G) varied from 50% to 300%. This is mainly due to two reasons: firstly, the overhead of beacon packet is more noticeable for the lower BO values since the beacon packets are more frequently transmitted; secondly, the frequent Clear Channel Assessment (CCA) in lower SO values could cause more collisions at the start of each superframe. For higher offered loads, the network throughput reached the relative saturation level that in their case, is approximately 62%. The success probability, however, drastically dropped as the offered load has increased. The offered G of lower than 50% own the highest probability of success rate when the SO$\geq$1. The difference between their conducted research and our simulation study is the lack of consideration of varying WBSN density, and the impact of interference on network performance gains. Furthermore, the values of CSMA/CA parameters (i.e. macMinBE and macMaxBE) were constant throughout their simulation study, whereas, in our simulation study, various values for macMinBE and macMaxBE are considered. Please note that the attained results presented in [24] did not match with the mathematical model proposed by the authors. Therefore, Park et al. proposed an improved Markov model to fully represent the behaviour of the CSMA/CA strategy being followed in IEEE 802.15.4 standard [25].

Some other researchers had performed the analytical evaluation of the CSMA/CA performance operated in IEEE 802.15.4 MAC layer [26, 27]. They have proposed a Markov model that predicts the behaviour of the slotted slotted CSMA/CA mechanism being performed by IEEE 802.15.4 standard. However, the simulation results failed to match with their proposed Markov model. Therefore, a detailed analytical evaluation of the CSMA/CA performance in IEEE 802.15.4 is proposed in [28]. Pollin et al. present a Markov model that predicts the behaviour of slotted CSMA/CA mechanism being performed by IEEE 802.15.4 standard. The obtained results were further compared to the simulation results (the Monte-Carlo simulation procedure) to verify their accuracy. Their analysis was inspired by [26, 27] but only for the usage of a per user Markov model. In [28], the state of each user at a particular moment was retrieved. Pollin et al. proposed a Markov model that not only fully reflects the behaviour of the CSMA/CA mechanism for IEEE 802.15.4 but also it is verified by looking at the simulation results. They have conducted an analytical study on the performance of CSMA/CA in both saturation and unsaturation networks. It is concluded that the larger macMinBE values is more suitable for saturated network, whereas smaller values of macMinBE could slightly improve the energy consumption in unsaturated networks. The probability of sending packets in different scenarios are varied accordingly. It is shown that the probability of sending packets is higher in saturated traffic when no acknowledgement packet is deployed. However, due to higher collision probability, the network throughput is very low. Although smaller number of packets are sent in periodic scenarios with unsaturated traffic, more throughput is achieved due to lower collision probability. In the aforementioned studies, the impact of internal interference on the performance of sensor network was not considered Which is the key difference compared to our study.

Previous mathematical models (Markov chain models), were offered in a memory-less fashion. This has caused the analytical models to be unable to fully represent the characteristics of the unsaturated WSNs (where sensor nodes do not always have data packets to transmit). Therefore, Ling et al. proposed another analytical model called “a renewal analytic model” that addressed the observed limitations in previous mathematical models [29]. In their proposed analytical model, it is assumed that the probability of starting to sense the channel (in a randomly selected slot) is fixed for each node and all sensor nodes attempt to re-transmit their data packets until they succeed. The results show a dramatic decrease in throughput while the average service time –the fraction of time between the moment that the data packet is located at the head-of-line and the time instance that it is removed due to either successful transmission, exceeding the maximum re-transmissions or exceeding the maximum number of consecutive CCA failures– represents the opposite trend as the number of sensor nodes increases. This is mainly due to small value of macMinBE = 3 and the macMaxBE = 5. Please note that according to IEEE 802.15.4 standard draft, both values are the default values for the macMinBE and the macMaxBE. Moreover, the backoff slots are uniformly distributed over a relatively short range of [0,31] which results in the execution of concurrent channel sensing by multiple sensor nodes as the network size increases. This would finally result in higher throughput degradation.

Lee et al. improved the previously introduced renewal model and made it applicable for unsaturated IEEE 802.15.4-based networks including acknowledgement packets [30]. Frame-dropping (due to transmission failure) is also considered in their proposed analytical model. The collected results indicate that, as the packet-arrival ratio increases, the probability of data packet dropping increases as well, which consequently results in dramatic decrease in successful transmission. Another interesting achievement of their study is that increasing the number of sensor node could result in experiencing larger average service time while the throughput follows the opposite trend. When the network size is small (e.g. $N = 5$) the throughput drops as both values of macMinBE and macMaxBE become larger. The throughput, however, follows an upward trend as the network size becomes larger (e.g. $N = 10$). This is because when a sensor node attempts to transmit a data packet, in the small network size scenario, it spends unnecessary amount of time for backoff purposes (large number of macMinBE and macMAxBE), whereas in the larger network size, spending larger amount of time becomes necessary to avoid collisions. Therefore, as the number of sensor nodes increases, it is expected to encounter higher throughput as well. Although Lee et al. have considered the impact of internal interference on the performance of CSMA/CA indirectly, the interaction between CSMA/CA internal parameters and other IEEE 802.15.4 system parameters have not been taken into consideration. This has made our study to be fairly different with the research conducted by them.

A Markov chain analytical model that covers both slotted and unslotted CSMA/CA mechanisms is proposed in [31]. In the proposed model, both node model and channel model are integrated into one model. Considering the achieved results, the throughput increases as the number of states became larger, while keeping the data transmission constant in value (314 bit). This means that for the constant data transmission, the collision probability decreases as the number of states increases. Interestingly, as the number of states increases, it becomes highly likely to detect the busy channel in the first CCA attempt. However, according to second CCA attempt, the probability of sensing the busy channel shows the downward trend. Please note that, the value of data packet transmission was fixed during the first and the second CCA attempts. OPNET network simulator was used to validate the accuracy of the results obtained from the analytical model. In their considered scenario, the values of system parameters were fixed throughout.

"Linear Increase Backoff" (LIB) is the modified slotted CSMA/CA mechanism proposed in [32]. LIB is designed based on an accurate Markov chain model. The main goal of LIB is to evaluate the performance of unsaturated, unacknowledged, one-hop star topology IEEE 802.15.4 MAC protocol operating in beacon enabled mode. More specifically, the LIB targets to identify the possible congestions, improve the latency and delay while maintaining the energy efficiency and throughput at the reasonable levels. According to their analytical and simulation results, the probability of sensing the channel as the busy channel in the first CCA attempt increases significantly as the number of nodes and the unit backoff period become larger. However, the probability of sensing the busy channel in the second CCA attempt is less sensitive to the unit backoff period but increases with the number of nodes. The simulation results for throughput indicate that the value of the first backoff counter plays a key role to determine the throughput. The small backoff counter causes the sensor nodes to start sensing the channel simultaneously which eventually results in higher collisions. On the other hand, configuring a too large value for the backoff period would also result in lower throughput due to aggregation of the large number of packets at the slot boundary. This implies that sensor nodes are required to wait for longer backoff period before sensing the channel. The study fully presented the dependability of the throughput on the number of active nodes and the unit backoff period. However, their interactions with other system parameters are not considered.

Many analytical models for CSMA/CA mechanism in IEEE 802.15.4 MAC protocol have been proposed to reduce the energy consumption of sensor nodes by improving the CSMA/CA mechanism. An energy conserving model is proposed to enhance the energy consumption while performing the CSMA/CA mechanism under the particular assumptions [33, 34]. A stochastic model for CSMA/CA, where the performance is evaluated based on the collision windows, is proposed in [35]. It is shown that the energy consumption of the sensor nodes is investigated when the CSMA/CA algorithm is performed. According to the obtained results, the sensor lifetime can be drastically decreased for the CCA higher than the 30%.

Many investigations are conducted to determine the effectiveness of the role of traffic loads on the CSMA/CA and eventually the sensor network performance gains. Baz et al. proposed two algorithms to improve the CSMA/CA functionality [36, 37]. Their proposed CSMA/CA mechanism contains two strategies namely: *selective frame* strategy and *selective frame* strategy. Each strategy is deployed based on the network-density and the size of data packets. They have also proposed a versatile approach to model the CSMA/CA protocol for IEEE 802.15.4 based on the theory of compound probability distributions [38]. According to the latter study, it is revealed that the lowest service time and the least energy consumption accompanied with non-stable throughput are the main characteristics of the unacknowledged mode. Additionally, “Limited” and “Unlimited” number of data packet re-transmissions could result in the improvement and reduction of the stability of throughput, respectively. A priority-based / service differentiated, adaptive algorithm is proposed in [39] to increase the “Quality of Service” for slotted CSMA/CA mechanism where the backoff exponents are initialised dynamically according to traffic variations. The simulation results indicate the significant improvement of success rate, effective data rate and average delay. A major defect of standardised CSMA/CA algorithm is shown in [40]. It is shown that assigning the length of backoff period without considering the current channel condition could degrade the overall performance gains. Moreover, adaptive backoff determination and priority-based service differentiation are the two contributions mentioned in their research.

The above-mentioned state of art discussed about the criticality of the CSMA/CA internal parameters (more specifically macMinBE and macMaxBE) and their impacts on the overall performance gains. We now focus on other system parameters and their impacts on the WSN/WBSN performance gains. Several studies have been conducted to determine the impact of various system parameters on the overall WSN/WBSN performance gains. Golmie et al. have studied the performance of IEEE 802.15.4 in the presence of internal and external interference [41]. According to the obtained results, although the end to end delay of high data load (1500 bytes) decreased significantly, the “goodput” dropped dramatically as the number of transmitters became larger. This was mainly due to the partitioning of the big data packets into the smaller size and waiting for the opportunity to transmit them to the receiver during the current and upcoming CAPs. This decreases the average end to end delay. Please note that in their configuration, if the transmission of a single partition failed, the remaining partitions would be deleted from the queue. This would result in a lower success rate compared to other traffic loads. In the second phase of their study, two WPANs (each consists of four medical applications) are considered for each patient. Both WPANs are configured to utilise the same operating frequency. The results indicate the significant packet losses for high traffic loads as the number of transmitters was increased.

The configuration and the optimisation of the network setup are discussed [17]. In the simulated scenario, a patient uses an ElectroCardioGram (ECG) and blood analysis module to study the protocol parameters for the network behaviour optimisation as well as lowering the energy consumption. In that study, the impact of varying values of the BI parameter on energy consumption, packet loss ratio, medium access delay and packet transmission retries is investigated. According to the simulation results (where BO = SO), the BO values lower than 3 consume more energy compared to higher values. This is mainly due to relatively high network traffic load (56192 bps) and short superframe duration which eventually results in deferring data packets to the next BI. This could

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increase the probability of packet collision at the first time slot of the next BI. Therefore packets will be lost and higher packet re-transmission ratio will be expected. Thus, higher energy consumption is inevitable. The same reasoning is applied for the packet loss ratio. Although, they have configured the commonly-used values for some network parameters (as in [41]), the impacts of interference caused by multiple neighbouring WBSNs as well as various values for data packet generation and CSMA/CA internal parameters have not been taken into consideration.

In [42] the impact of various system parameters such as packet arrival rate, number of sensors, buffer-size, packet size and inactive periods. The results indicate that the average access delay (even for small buffer-size) becomes very large if the throughput exceeds 50%. In order to achieve even higher throughput, the larger buffer-size is required. They have also investigated the impacts of packet arrival rate, buffer size, packet size and the inactive period on the IEEE 802.15.4 network performance gains with another set of performance measures, [43] namely: The probability of access probability that the medium is idle; and the blocking probability were considered as the main performance measures. According to the obtained results, either the network size or packet arrival rate must be carefully determined in order to avoid higher blocking probability (the probability that a packet will be blocked due to insufficient capacity of the device buffer during the backoff period). Furthermore, the study indicates that the larger buffer size would provide the opportunity of increasing both packet arrival rate and number of stations.

The challenges and issues caused by various system parameters, e.g. packet arrival patterns (Poisson or periodic), different values of CSMA/CA parameters, BI, various packet size and different offered loads are investigated in [44]. The results indicate that when data packets are generated periodically, all nodes compete to access the channel at the beginning of the active period which results in less delivery ratio. On the contrary, in scenarios where Poisson data arrival pattern is utilised, not all nodes have to contend for channel access at the beginning of the CAP. However, the contention is more likely to happen even when the CAP length is relatively small compare to BI length. This infers that the IEEE 802.15.4 MAC layer has difficulties to handle the contention efficiently. Although a wide range of system parameters and their impacts on WSN performance gains is considered in their study, their research lacks the impact of the above-mentioned effective system parameters in the presence of intensifying internal interference which is the key difference compared to our simulation study.

Clearly, data packet delivery ratio is directly related to the size of the CAP (SO) and the length of the BI (BO). As mentioned earlier, the contention is more likely to happen when the CAP is relatively small compared to the BI length. Long BIs might also cause the buffer overflow and eventually discarding the data packets. Therefore, it would be really helpful to dynamically adjust the values of SO and BO based on the traffic load. An investigation is conducted to determine the impact of MAC parameters such as BO and SO [45]. The performance of IEEE 802.15.4 MAC protocol using the *DYMO* protocol is evaluated where the values of BO and SO were dynamically adjusted based on traffic loads. The attained results indicate that as the data rate per packet increases, the throughput drops dramatically. Moreover, for all values of BO = SO, the throughput is noticeably low. “Superframe Adjustment and Beacon Transmission Scheme” (SABTS) is proposed to solve the beacon collisions (collision with each others and with data frames) [46]. The accurate values are assigned to BO and SO of PAN coordinator, cluster coordinator and sensor devices in cluster tree topologies. The results from analytical and simulation-based studies show higher successful transmission and lower energy consumptions in comparison to bare IEEE 802.15.4 standard. It must be noted that the length of active period for the PAN coordinator is fixed and is configured to cover the whole BI (SO = BO). Although the proposed approach has significantly improved the sensor network performance gains, such approach is designed for cluster-based tree topologies and may not be applicable on random independent neighbouring WSNs. Figure 2 depicts the process of SABT in the form of a flowchart.

Another application that seems to be useful for initial configuration of IEEE 802.15.4 X-MAC parameters is *pTune*. pTune is a layered model designed to receive the network requirements such as network life time, end-to-end reliability and end-to-end latency as inputs and offers the optimised values for IEEE 802.15.4 X-MAC parameters [47]. The proposed model responses to occurrence

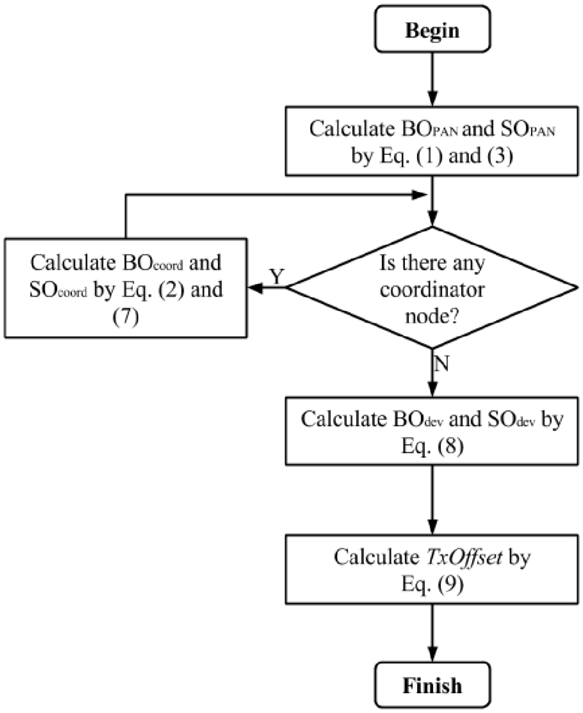

Figure 2. The SABT flow process

of some issues such as insufficient bandwidth, energy consumption as the peak traffic loads, Traffic loads fluctuation and poor link quality by adjusting the X-MAC parameters values. However, how they could manage to accomplish the mentioned responses is not discussed in their article. Figure 3 depicts the pTune framework.

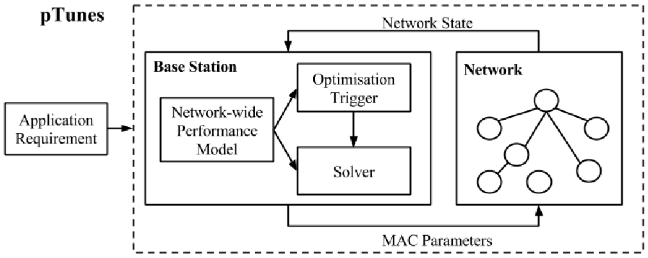

Figure 3. The pTune framework

The presence and absence of hidden terminals could also play an important role in the overall performance gains. The impacts of IEEE 802.15.4 MAC parameters namely: macMinBE, macMaxBE, macMaxCSMABackoffs and frame re-transmission on MAC protocol performance are analysed in [48, 49]. In their study, the traffic loads and the interference caused by neighbouring nodes varied in the presence and absence of hidden terminals. The objective of their study was to determine the proper values for MAC parameters in order to come up with the acceptable level of trade-off between success rate and the latency for the given range of the traffic loads. They have shown that at the lower traffic loads and the absence of hidden terminals, increasing the BE value could result in the lower packet loss rate. Moreover, higher collision probability and packet loss rate would be experienced as the number of hidden terminals becomes larger for all values of "macMaxBE". According to the frame re-transmission results, it could be observed that any increase in frame re-transmission value beyond 1 does not cause any noticeable changes in the packet loss rate in the absence of hidden terminals.

A hardware-experiment is conducted to evaluate the performance of IEEE 802.15.4 [50]. The effects of four elements on the performance gains of IEEE 802.15.4 were determined. These four elements and parameters are: 1) direct and indirect data transmission; 2) CSMA/CA; 3) data payload size; 4) beacon-enabled mode. The sensor devices and the coordinator formed a star topology where the sensor device 1 continuously sends and receives packets to and from the coordinator and the other 3 sensor devices are the traffic load generators. Figure 4 depicts the designed star topology.

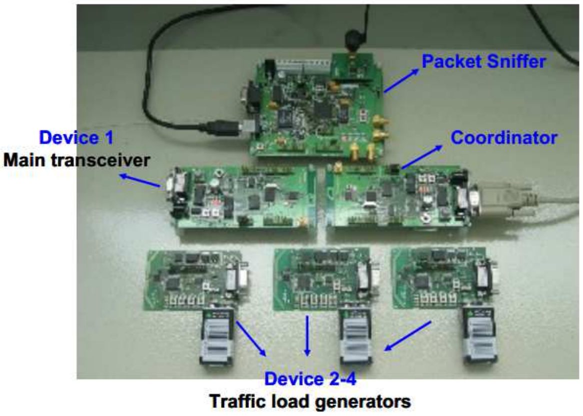

Figure 4. The star topology of the experiment conducted in [50]

According to their obtained results of the non-beacon enabled mode, the indirect data rate (the transmission from coordinator to the sensor device 1) is noticeably below the direct data rate (from the sensor device 1 to the coordinator). This is mainly due to the sensor devices polling rate (sending request periodically). The second set of results shows the impact of low macMaxBE and macMinBE values: 4 and 3, respectively. It is shown that as the number of active devices becomes larger, the delivery ratio will be decreased due to data packet collisions. Moreover, with the larger traffic loads being transmitted by other devices the delivery ratio shows the downward trend. This is again due to possibility of the collision occurrence. The impact of data payload size on the performance gain is determined in the third experiment. The result shows that as the payload size increases, the delivery ratio is decreased due to higher probability of collisions. In all conducted experiments the BO = SO = 15 which represents the non-beacon enabled mode. However, according to the last experiment which determined the effect of beacon-enabled mode, the values are both BO and SO varied from 1 to 15. The delivery ratio of the data packets is not considered in their obtained results, and only the effective data rate diagram is shown. It is then concluded that the non-beacon enabled mode experience higher effective data rate.

Duty cycle is also considered as one of the effective system parameters on WSN performance gains. “Reinforcement Learning” method is offered in [51] to determine the best duty cycle of the particular BI. The aim of the proposed algorithm is to minimise the human intervention for re-configuring the duty cycle in order to fulfil the specific requirements of different networks. The results indicate that although “AMPE” [52] approach selects the same duty cycle as DCLA does, more processing overhead is incurred on micro-processor as it carries out more frequent CCAs. According to the AMPE algorithm, it is assumed that the duration of time that the channel is busy associates to the superframe occupation and is totally related to the traffic load factor. Therefore the amount of time that the channel is busy (during the active period) could be determined using the *PLME-CCA* request primitive offered in IEEE 802.15.4. However, this primitive requests are required to be invoked by sensor devices repeatedly within superframe duration. Although, CCA measurement seems to provide more accurate information rather than the estimation strategies, considering each CCA measurement lasting only 8 symbols, results in noticeable energy consumption in the sensor devices. This makes this approach less interesting. For more detailed information about the network performance comparison between DCLA and other schemes that deal with duty cycle, such as Beacon Order Adaptation Algorithm (BOAA) proposed in [53], and Duty Cycle Algorithm (DCA) proposed in [54] to enhance the IEEE 802.15.4-based MAC protocol please refer to [51]. The BOAA scheme uses certain number of transmitted message by the sensor devices in order to estimate the network offered load. Such received messages are maintained in the form of matrix which infers memory occupation and becomes problematic when dealing with large networks. However, the DCA exploits extra information such as transmit queue occupation and end-to-end delay in their duty cycle in order to determine the proper duty cycle. Table I briefly provides the information related to the major system parameters, the performance measures and the evaluation method and tools according to each and every of aforementioned state of the art.

3.2. Probable Solutions

Channel Coexistence is considered as one of the most important challenges in IEEE 802.15.4. Several investigations have been conducted to study and evaluate the performance of the wireless systems when the spectrum is utilised either homogeneously or heterogeneously. In this part, we highlight the latest approaches that have addressed the challenges regarding to homogeneous coexistence of IEEE 802.15.4-based wireless sensor networks. One of the key ideas to resolve the issues caused by channel coexistence (e.g. internal interference) is to make the system more flexible with dynamic operating frequency allocation. The main goal is to minimise the packet collision caused by multiple IEEE 802.15.4-based systems that are using the same operating frequency at the same time. The first step towards tackling the internal interference is to employ an interference detection techniques: *Energy Detection*, which is done through CCA attempt offered in IEEE 802.15.4 and uses the “Received Signal Strength Indicator” (RSSI) service (in PHY layer) [55, 56]. The RSSI measurement may suit well to detect the interference caused by WiFi technology as the traffic load continuously exist and different carrier sensing strategy is deployed. However, deployment of such measurement does not provide reliable information about possible interference in homogeneous WSNs with periodic transmission. *Packet Error Rate* and *Link Quality Indicator* measurements are also considered as the other two popular and commonly used interference detection techniques [57]. Many researches have been conducted to determine the efficiency of the above-mentioned interference detection techniques. For in-depth information about the efficiency of such techniques please see [58, 59]. Several schemes and approaches have been proposed by researchers to alleviate the destructive effects of external interference (mostly caused by WiFi technology) on the performance gains of WSNs/WBSN [60, 57, 61]. However, In this survey we only focus on the impacts of internal interference on WSN/WBSN’s performance gains.

The IEEE Standard for Local and metropolitan area networks (WBAN) [62], has recently been standardised to address the critical requirement of health related application in the field of wireless body sensor networks. IEEE 802.15.6 MAC protocol has introduced four strategies to mitigate the interference caused by neighbouring BANs: 1) Beacon-shifting, where the shifting offset is included in the beacon packet. The coordinator must select the proper shifting offset to avoid further beacon collisions. 2) Channel Hopping, could be only enabled in narrow band with PHY not operating in the Medical Implant Communication Service (MICS) or a frequency modulation of Ultra-Wide band. In the above-mentioned cases, upon including the certain information in the beacons, the coordinator may change its operating frequency periodically. 3) Active Superframe Interleaving, where a Body Area Network (BAN) is able to negotiate with other BANs to share the same operating frequency through sending command-active-super-frame-interleaving-request frame in the beacon enabled mode BANs. 4) B2-aided time-shifting, where the functionality is similar to Active Superframe Interleaving, and is only applicable for non-beacon enabled mode.

Although the IEEE 802.15.6 MAC protocol is specifically designed to address body sensor networks, we have not simulated this technology simply due to being currently commercially unavailable which makes this standard arguably immature. The above-mentioned strategies could solve the problem of channel coexistence but only to some extent. For example, when the number of

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Table I. The analogy of State of art in terms of utilised system parameters

	System parameters	**Performance Measures**	**Evaluation Methods and Verification Tools**
[17]	BI(BO) and packet transmission retries	energy consumption, packet loss ratio, medium access delay	OPNET simulator
[41]	number of transmitter in homogeneous and heterogeneous networks	end to end delay, goodput	OPNET simulator
[24]	slotted CSMA/CA algorithm, BO and SO	throughput and average delay and probability of success	analytical modelling
[25]	slotted CSMA/CA algorithm	throughput, average delay and probability of success	Markov model and ns_2 simulator
[28]	saturated and unsaturated sensor nodes in beacon-enabled and non-beacon enabled modes CSMA/CA internal parameters	CSMA/CA performance	analytical modelling (Markov model) and (Monte-Carlo simulation procedure)
[42]	packet arrival rate, number of stations, the finite size of individual node buffers, packet size, inactive period between the beacons and CSMA/CA internal parameters	average access delay and throughput	analytical modelling (Markov model)
[43]	packet arrival rate, number of stations, station buffer size, packet size and inactive period between the beacons	probability of access, probability that medium is idle, queue length distribution in the device, and probability distribution of the packet service time	analytical modelling (Markov model)
[29]	number of sensor nodes and CSMA/CA algorithm	throughput and MAC service time	analytical modelling (Markov model)
[30]	network size and CSMA/CA internal parameters	packet-arrival ratio, the probability of data packet, average service time, throughput and success rate	analytical modelling and C++ language based simulation code
[31]	slotted and unslotted CSMA/CA mechanisms and integration of the node and the channel	collision probability and throughput	analytical model and OPNET simulator
[32]	modified slotted CSMA/CA mechanisms	latency and delay, energy efficiency and throughput	analytical model (Markov model) and ns_2 simulator
[33, 34]	number of nodes and CSMA/CA mechanism	Energy efficiency of CSMA/CA algorithm and throughput	analytical modelling and C++ language based simulation code
[36]	ack and non-ack mode with both saturated and unsaturated traffic pattern, CSMA/CA mechanism	throughput, average delay, collision rate, buffer occupancy and offered load	bespoke simulation platform
[38]	number of nodes, slotted CSMA/CA algorithm	throughput, average MAC service time, successful transmission and energy consumption	Analytical Model (Markov model) and A particular simulator designed by author
[39]	number of sensor devices, different priority levels for different sensor devices (service differentiated) and adaptive CSMA/CA internal parameters values	average delay, effective data rate, and packet loss rate	IEEE 802.15.4 module included in the OMNeT++ simulator
[40]	number of sensor devices, different priority levels for different sensor devices (service differentiated) and adaptive CSMA/CA internal parameters values	collision probability and mean end-to-end delay	IEEE 802.15.4 module included in the OMNeT++ simulator
[44]	number of sensor devices, power management mechanism (always active or not), periodic or poisson packet arrival patterns, frame re-transmissions, BI, CSMA/CA parameters	delivery ratio, latency, on-time delivery ratio average energy per packet	Gilbert-Elliot model and ns_2 simulator and real test-bed experiment
[48, 49]	macMinBE, macMaxBE, macMaxCSMABackoffs, frame re-transmission,traffic loads and interference caused by neighbouring nodes	packet loss probability and the packet latency	Simulink or NS-2 and the real test-bed experiment
[47]	low and high traffic loads varying link quality and generally MAC parameters	network lifetime, end-to-end latency and end-to-end reliability	test-bed experiment
[50]	the direct and indirect data transmissions, CSMA-CA mechanism, data pay load size, and beacon-enabled mode	data throughput, delivery ratio, and RSSI	real test-bed experiments
[46]	inter-arrival time	probability of successful transmission, the probability of collisions, network gudput and energy consumption	Markov model and ns_2 simulator
[51]	network offered load, number of sensor devices and duty cycle	energy efficiency, end-to-end delay and probability of successful transmission	OPNET simulator
[52]	SO and the traffic-load factor	efficiency of the proposed algorithm, throughput, and coordinator energy consumption	Network Protocol Simulator (NePSing)
[53]	BO, time scale,	the average power consumption to the power consumption in receive mode, service delay and BO	Simulation (not specified)
[54]	number of sensor devices	energy consumption(sensor and coordinator), SO variance, number of packet dropped, end-to-end delay and successful transmission	ns_2 simulator

active WBANs are relatively small, utilising the beacon-shifting approach assists WBANs to adjust their beacons to avoid active period overlapping.

A flexible beacon scheduling scheme is proposed in [63] where coordinators have to perform the carrier sensing before the beacon transmission. Their proposed approach is then compared with the beacon-shifting approach offered in IEEE 802.15.6 MAC protocol. The results indicate significance improvements in terms of successful transmission over the beacon-shifting strategy. Another simulation study was conducted to compare the performance of IEEE 802.15.4 with IEEE 802.15.6 [64]. The simulation study indicates that IEEE 802.15.4 outperforms the IEEE 802.15.6 in terms of throughput. In our previous studies we have evaluated the performance of IEEE 802.15.4 MAC protocol to find the potential white spaces [65, 66]. The channel utilisation is classified into three – white, grey and red – regions, which represent if a given channel is idle, being used by one user or overlapped with two or more neighbouring WSNs, respectively. Figure 5 represents the channel utilisation classifications.

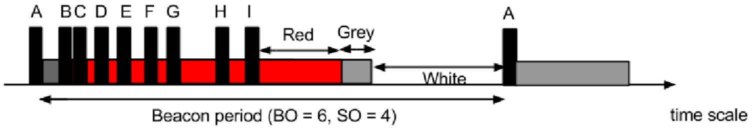

Figure 5. The channel utilization characteristics

We have studied the percentage of channel utilisation as the network density increases. Preliminary schemes are proposed (blind, Idealised, Initial choice and Greedy) to detect the existence of overlapping neighbouring networks without the need for a centralised coordination infrastructure. The Greedy scheme enabled the WSNs to adapt their schedule in order to minimise the red region. Nevertheless, the Greedy has its drawbacks. As the number of networks per channel increases, the amount of gaps would decrease. Therefore the arrival of additional networks would result in their starvation in terms of channel access. Later scheme introduced frequency adaptation feature [67]. Frequency adaptation feature enables WSN/WBSN to switch to a channel with the lowest interference. Whereas the aforementioned Greedy scheme assists WSNs to utilise the currently-occupied operating frequency, more efficiently. In frequency adaptive schemes the coordinator actively takes samples from each channel during the inactive periods. This samples reveals the information of the occupancy-load of each and every available channels. Although this would increase the energy consumption of the coordinator, the attained information is definitely useful when a WBSN decides to switch to the other channel. The coordinator assesses the quality of the current channel in order to decide whether to stay on the current channel or to hop to another one. Therefore, two channel-quality assessment strategies were offered to the coordinators: periodic-assessment and continuous-assessment. According to the periodic-assessment strategy, the coordinator waits for a specific period of time and then assesses the channel-quality. Whereas, according to continuous-assessment strategy, the coordinator actively assesses the channel-quality. This enables the coordinator to switch to the other channel at the exact time that the channel-quality has degraded below the threshold [68]. A new study has shown that phase-shifting strategy can be effectively useful to improve the performance gain of WBSNs [69].

“Cognitive Radio” (CR) networks provides the opportunity of sharing the same frequency spectrum with *Primary Users* (PU) of the that particular frequency spectrum in on opportunistic manner. CR users are equipped with the dynamic spectrum access capability that allows them to identify the portion of the spectrum which is available for potential transmissions. This technology is designed to address the channel scarcity in the 2.4 GHz ISM band where the frequency spectrum is inefficiently utilised. It must be noted that in CR technology, the PU transmission must be left unharmed. This implies exchanging essential information in order to assure the spectrum availability between the given pair of nodes before commencing the data transmission. Since this information exchange is considered to be the MAC protocol responsibility, several researches have highlighted the problem of MAC protocol for CR networks and proposed effective solutions to maximise the coexistence of both homogeneous and heterogeneous technologies in the same frequency spectrum [70, 71]. Although their proposed solutions may suit well with the requirement of the CR users, they are not suitable for unlicensed 2.4 GHz frequency spectrum where a large number of homogeneous wireless technologies (i.e. WBSN) attempt to utilise the same frequency spectrum without any priority consideration in advance.

Using “multi-channel MAC protocol” strategy is another approach for reliable data packet transmission in the presence of internal interference. Utilising the Request To Send (RTS) and Clear To send (CTS) in CAP and modifying them (adding extra sub-field) have resulted in smaller average end-to-end delay [72]. However, it is highly likely that adding these two packets in the CAP would cause collisions as the number of active WBSNs increases. Besides it is not clearly mentioned that how a sensor device is provided the information regarding other channels status (either free or busy). A survey of using multi-channel strategy is provided in [73]. The main goal of deployment of multi-channel approach is to offer more reliable data packet transmission [74]. Light traffic and small number of active WSN/WBSN are the main assumption for these proposed approaches.

Single fixed channel approaches are commonly used in WSN applications, mainly due to their simplicity and lower power consumption [75]. However, nowadays many low-power sensor network nodes are equipped with radio transceivers capable of operation on multi-channels and/or multi-bands [76, 77, 78, 79, 80]. One of the objectives of multi-channel MAC protocols is to increase the throughput of network in the presence of internal interference. The drawback of such protocols is that under light channel interference they are less energy-efficient in comparison to single-channel protocols. An energy efficient multi-channel MAC protocol for WSN, called Y-MAC is proposed in [81]. Y-MAC is capable of achieving high performance while being energy-efficient for both moderate and high traffic conditions when the performance of sensor networks are threatened by internal interference. Using multiple transceivers on a WSN device increases the total performance gains and reduces the energy consumption. However they could be achieved at the price of higher costs and complexity. Whereas lower costs and complexity along with smaller size of the sensor devices are the important factors that should be given a serious attention when dealing with WBSNs.

The concept of “Virtual Channel” is introduced in [82]. Virtual channel strategy is meant to provide the opportunity of increasing the number of available channels through efficiently managing the given spectral and temporal resources. In this approach, the throughout estimation of the IEEE 802.15.4 CSMA/CA is fed to a superframe scheduler. Thereafter, the selecting of the logical channel accompanied with the superframe scheduling approach would result in creation of a virtual channel. This approach requires a “management entity” to provide such information for up coming WSNs. The main shortcoming of the central management approaches is when the manager entity becomes out of order the whole system encounter a great deal of agitation. “Dynamic Channel Allocation” (DCA) is proposed in [83] to minimise the interference caused by neighbouring sensor nodes. The DCA is based on what is proposed in graph colouring. In this approach, the colour repetition occurs only if the nodes are separated by more than 2 hops. The DCA tends to assign optimally the minimum channels in a distributed manner. Once the channel is assigned the desynchronised multi-channel MAC (CMAC) takes over the responsibility of the conventional MAC protocol. The CMAC allows the maximum possible sleep time, prevents overhearing and offers the minimal control overhead. However, the maximum number of sensor nodes under investigation is 10 sensor devices which is relatively a small number to study the internal interference.

Table II presents some of the latest proposed approaches and offered strategies to mitigate the destructive impact of internal interference in homogeneous WSNs.

Several surveys can be found that address the challenges and probable solutions in the area of WSNs/WBSNs/WBANs [87, 88, 89]. Some of them provide readers with the general overview of application, functional and technical requirements of the BAN [90, 91]. Some other surveys highlight present the overview of the characteristics and limitations of the sensor nodes that are commonly deployed in the WBSNs [92]. Many surveys have focused on the application point of view with the special emphasis on medical and health-related aspects. They have also revealed the issues encountered by healthcare systems [93, 94, 95, 96]. For instance, patient-mobility could be considered as a potential issue in the hospital while wearing a WBSN. Therefore, Caldeira et al. have surveyed the handover strategy for intra-mobility where the sensors are able to move around within the same network domain but different access points [97]. Carrano et al. have focused on the energy consumption of the sensor nodes through managing the duty cycle [98], while Sudevalayam et al. have considered the applicability of the energy harvesting techniques on WBANs using the human body as the source of energy [99]. Khanafer et al. have focused on some strategies to mitigate the impact of interference on performace gains [100]. However, in contrast to the above-mentioned surveys, this paper specifically deals with the internal interference caused by neighbouring WBSNs. More particularly, the impact of system parameters on WBSN’s performance gain is investigated

Table II. The analogy of State of art in terms of proposed approaches and strategies

	Problem Statement	**Proposed solution**	**Evaluation Methods and Verification Tools**
[62]	channel coexistence	beacon-shifting, channel-hopping and active superframe interleaving	Not specified
[63]	channel coexistence	flexible beacon scheduling scheme for IEEE 802.15.6	Castalia 3.2 simulator
[64]	channel coexistence	comparison between IEEE 802.15.6 and IEEE 802.15.6	Castalia 3.2 simulator
[65]	internal interference in homogeneous WBSNs and channel scarcity	initial-choice and idealised schemes (introduced as upper band)	Castalia 3.2 simulator
[66]	internal interference in homogeneous WBSNs and channel scarcity	greedy channel utilisation approach	Castalia 3.2 simulator
[67]	internal interference in homogeneous WBSNs and channel scarcity	continuous-hopping approach	Castalia 3.2 simulator
[68]	internal interference in homogeneous WBSNs and channel scarcity	continuous-assessment vs periodic-assessment	Castalia 3.2 simulator
[69]	internal interference in homogeneous WBSNs and channel scarcity	Adaptive phase-shifting approach	Castalia 3.2 simulator
[70]	channel assignment problem	segment-based channel assignment strategy	analytical and simulation
[71]	low performance gains due to channel coexistence	coexistence-aware spectrum sharing protocol	analytical and simulation
[84]	low performance gains due to channel coexistence	coexistence detection and coexistence mitigation strategies	OPNET simulator
[85]	low performance gains due to channel coexistence	dynamic coexistence management (DCM) mechanism	OPNET simulator
[86]	low performance gains due to channel coexistence	dynamic coexistence management (DCM) mechanism	test-bed experiment (Markov model)
[72]	low reliability and high delay due to internal interference	multi-channel MAC protocol approach	—
[73]	destructive impacts of internal interference on sensor network performance gains	advantages and disadvantages of various proposed multi-channel communication approaches	analytical modelling (Markov model)
[74]	increasing the nodes density and escalation of internal interference	an energy efficient multi-channel MAC protocol approach	test-bed experiments
[76]	coexistence with other technologies	multi-radio prototype	test-bed experiment
[77]	coexistence with other technologies	dynamic spectrum access strategy	test-bed experiment (Iris platform)
[78]	performance degradation due to spectrum congestion caused by increasing the popularity of wireless embedded devices	a low-power spectrum agile MAC protocol	analytical analysis and test-bed experiment (TelosB platform)
[79]	the current multi-channel MAC protocols are being inflexible to the variation of the environment	Dynamic Multi-radio Multi-channel MAC (DMMA)	test-bed experiment
[80]	performance degradation due to radio interference	coordinated channel switching and spectral multiplexing	test-bed experiment (Mica2 sensor nodes)
[82]	channel scarcity	scheduler using throughput estimation (SUTE), nearest vacancy search (NEVS)	ns_2
[83]	internal interference	dynamic channel assignment (DCA) and CMAC	JAVA based discrete event (SimJava)

from two perspectives: MAC parameters and protocol design. Furthermore, a simulation study has been conducted to clarify the impacts of MAC parameters on WBSN's performance gain in the presence of intensifying internal interference.

4. SIMULATION EXPERIMENT

The second contribution of this paper is to conduct a simulation study to evaluate the functionality of the IEEE 802.15.4-based WBSNs under intensifying internal interference. In this study, the impact of a set of MAC and application layer parameters on WBSN performance gains were evaluated as the WBSN-density was gradually increased. To accomplish this, *Castalia-3.2* network simulator was utilised to simulate the networks scenarios and to extract the necessary results [101]. Since we are interested in the impact of internal interference on the WSN/WBSN's performance gain, all the 16 channels are available for WBSNs only, and sharing this resource with other technologies are disregarded.

4.1. System Model

In our simulation-beased study, a single WBSN forms a star topology and consists of a stationary coordinator and four stationary sensor nodes placed equidistantly on a circle of 1 m radius around the coordinator. We have simulated a scenario in which δ static WBSNs, where $\delta \in \Delta$ and $\Delta =$

$\{50, 100, 150, 200, 250\}$ were placed at the same spot and their performance gains are investigated under varying parameter configurations. This arrangement implies that the size of the area in which WBSNs are located, is 2m × 2m squared area. Neither any type of node's mobility (within a WBSN or as a whole) nor shadowing by the human body is considered in our simulation-based study. Without the loss of generality, we have chosen this particular arrangement to eliminate hidden-terminal situations and packet losses coming from path loss or fading effects, and hence to get a clear view on the effects of internal interference coming from competing WBSNs – in this way packet losses can certainty be attributed to packet collisions. Additionally, locating all WBSNs at the same spot allows us to rule out the impact of different transmit powers. Thus, the packet collision can be directly attributed to the mutual interference caused by WBSNs on each other.

Each WBSN operates in the beacon-enabled mode and chooses its operating frequency according to one of the three schemes described below. Each transmitted data packet is acknowledged by the coordinator. If a sensor device does not receive an acknowledgement, it attempts to retransmit its data packet up to a specific number of retries. Furthermore, the sensors are configured to maintain synchronisation with the coordinator. This means that the sensors have to wake up and receive all beacon packets sent by their coordinator, and if the sensor has not received four consecutive beacon packets, it becomes ”orphan” and scans the frequency channels according to the considered scheme.

Each PAN coordinator is switched on at a random time using an exponential distribution with a mean value of 1 second. In order to determine the impact of MAC parameters, a candidate set of MAC parameters is introduced. BO, SO, macMinBE, macMaxBE and Data Generation ratio are the members of such set.

The following factors are selected for this simulation experiment:

- System load or packet inter-arrival time: we assume that sensors generate packets periodically and this period is configurable using the packet inter-arrival time. Since the in general the inter-arrival time and the beacon period are not completely independent of each other, as the beacon period must be smaller than the inter-arrival time for the latter to be meaningful. Therefore, the minimum inter-arrival time is chosen to be larger than the largest beacon period.
- Beacon order: the beacon order (BO) parameter determines the beacon period and therefore the overall rate of beacon transmissions.
- Superframe order: the superframe order (SO) determines the active period. The maximum and minimum values for the superframe order is selected in such a way that it can be combined with each of the beacon orders while satisfying the constraint $SO \leq BO$.
- The macMinBE and macMaxBE parameters are related to the collision-avoidance CSMA MAC protocol used by IEEE 802.15.4 in the uplink: before each carrier-sensing attempt the MAC layer waits for a random backoff time. This time is a multiple of a random integer drawn uniformly from the interval $[0, 2^{BE} - 1]$, where BE is the current backoff exponent. BE is initialized with *macMinBE* and increased each time the channel is sensed as busy, until the maximum value *macMaxBE* has been reached. Therefore these parameters define how aggressively a sensor accesses the channel.

Table III shows the considered values for the candidate MAC and application parameters.

Parameter	**Min value**	**Max value**
Application Layer Parameters		
Packet Inter-arrival Time	5 s	10 s
MAC Layer (CC2420) Parameters		
Beacon Order	4	7
Superframe Order	1	3
macMinBE	1	macMaxBE
macMaxBE	3	8

Table III. Factors and their Min/Max values

The attained results is divided into 4 categories, namely: 1)BO = 4, SO = 1, 2)BO = 4, SO = 3, 3)BO = 7, SO = 1, 4)BO = 7, SO = 3. The title of each scheme illustrated in the following diagrams

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represents the order of BO, SO, macMinBE, macMaxBE, Data Generation ratio, respectively. For instance, scheme title "4113_5" represents BO=4, SO=1, macMinBE=1, macMaxBE=3, data generation ratio=5 (one packet every 5 seconds), respectively. The active WBSNs (WBSN-density) are uniformly distributed over 16 available channels and is gradually increased to determine the destructive impacts of internal interference on WBSN performance gains. Three major performance measures are considered in our study namely: 1) *Energy Consumption*, which is the energy consumed by the transceiver of a sensor device and is the average of energy consumption of all sensor devices in all simulation runs. 2) *Success rate*, which is the the average percentage of the data packets that are successfully received by the coordinator and the acknowledgement packets are successfully received at the sensors side accordingly. 3) *Satisfaction rate* is the average percentage of number of WBSNs that experience above 95 % success rate (or in conversion less that 5 % packet loss). The simulation run is configured in such a way that at least 2000 data packets were generated.

4.2. Energy Consumption Model

One of the main concerns in the field of WBSNs is the energy consumption of sensor devices due to being energy constraint [102]. Energy consumption is considered as one of the major performance measures to evaluate the proposed schemes. In our energy-model, energy consumption (power consumption) of a sensor device is related to its transceiver and the power consumed by other components of a WBSN nodes is disregarded. The transceiver energy consumption is modelled using the characteristics of the IEEE 802.15.4 compatible with ChipCon CC2420 transceiver [103]. It is assumed that the power supply voltage and the transmit power are fixed to 3.3 v and -25 dBm respectively. In our simulation experiment, there are three operational states in a single sensor device: sleep, transmit and receive states, and the time spent in either of these operational states is collected individually. Thereafter, the collected time is multiplied with the average power consumption of that particular state. This would help us to compute the total energy consumption.

The coordinator starts the body sensor activity through going to transmit state and sending the beacon packets. The sensor device changes its state to the receive state to detect the beacon packet being transmitted from its corresponding coordinator. After extracting information from the beacon packet, the sensors attempt to access the channel by performing the CSMA/CA channel access mechanism to avoid possible collisions. When the safe time slot is determined, the sensor changes the operational state to transmit state, followed by transmission of data packet to the corresponding coordinator. The coordinator changes the operational state to the receive state after beacon packet transmission to receive possible data packets transmitted by the sensor devices. Each sensor device that has transmitted its data packet to the coordinator and received the correspondent acknowledgement, changes the operational state to sleep state. Both coordinator and sensor devices change their operational states to the sleep state at the end of active period to save up their energy during inactive period.

5. RESULTS AND DISCUSSION

5.1. BO = 4, SO = 1

As a reminder, satisfaction is defined as the average percentage of WBSNs that experienced over 95% success rate out of the given total number of WBSNs. Figure 6a depicts the satisfaction rate as the WBSN-density becomes larger. It is observed that as the value of macMinBE has the direct influence on the satisfaction rate and larger value of macMinBE results in higher satisfaction rate. Larger value of macMinBE results in longer back off period. This would consequently result in lower packet collision rate. It must be noted that in scenarios with large number of saturated active WSNs/WBSNs, larger values of macMinBE and macMaxBE would result in lower probability of collisions, whereas, in unsaturated scenarios, sensors must wait for longer period of time in backoff state and hence higher energy consumption is inevitable. Data generation ratio also seems to be influential on WBSN's performance as well. One packet generation every 5 seconds would result in lower satisfaction rate in comparison with the one packet generation every 10 seconds

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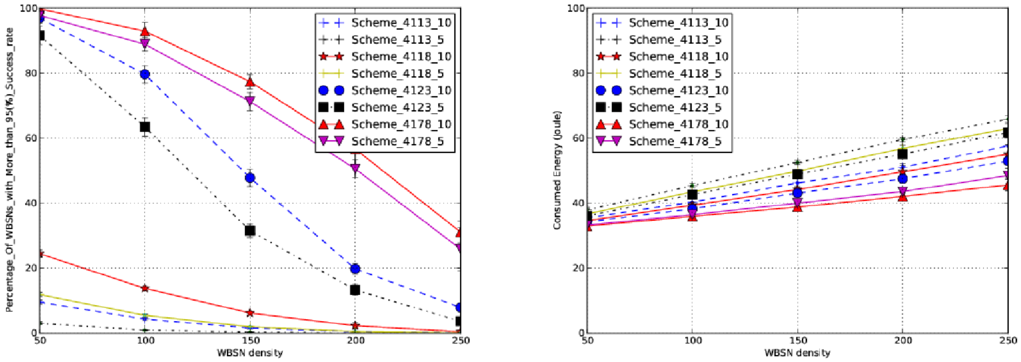
due to experiencing higher collision rate. According to figures 6b configuring larger values for macMinBE and macMaxBE, would result in lower energy consumption. This is mainly due to avoiding collisions and therefore less orphaning experience for a sensor node.



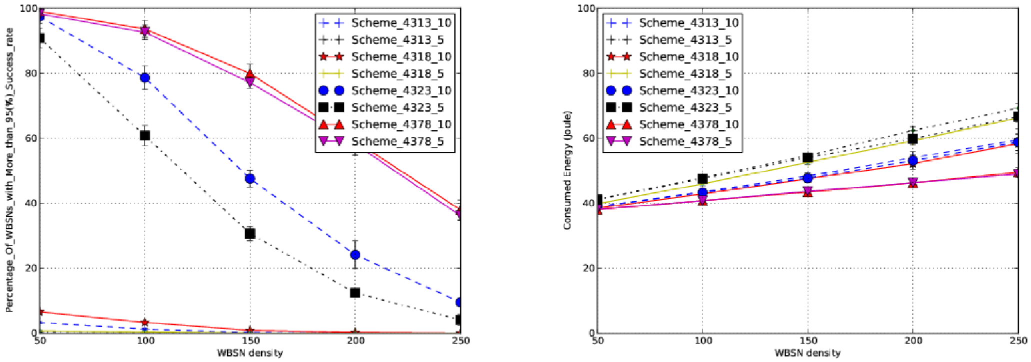
(a) Satisfaction rate

(b) Sensor energy consumption

Figure 6. Impact of various BO/SO on BSN performance

5.2. *BO = 4, SO = 3*

According to figure 7a, the satisfaction rate drops dramatically as the values of macMinBE and macMaxBE become smaller. Such dramatic downward trend is more visible compared to the previously introduced group (BO = 4, SO = 1). This is mainly due to high ratio of collision occurrence as the active period becomes longer. Considering figure 7b, higher energy consumption in comparison with previous group is due to the length of the CAP. On one hand, as the active period becomes longer, the probability of collision occurrence will be increased. Hence, higher packet loss ratio is expected. On the other hand, longer active period provides the opportunity of multiple data packet re-transmission which clearly would cause higher energy consumption. The coordinator energy consumption is directly being affected by the length of active period.



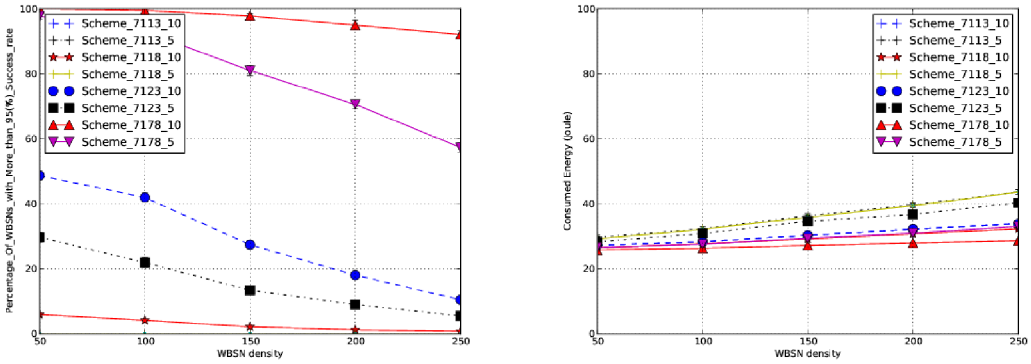
(a) Satisfaction rate

(b) Sensor energy consumption

Figure 7. Impact of various BO/SO on BSN performance

5.3. *BO = 7, SO = 1*

According to figure 8a significant drop in satisfaction rate is observed as the values of both macMinBE and macMaxBE become smaller. Larger values for macMinBE and macMaxBE makes sensor node to remain longer in backoff period and hence keeps the channel more stable. By comparing the satisfaction rate observed in this group with the corresponding diagrams in previously introduced groups, it could be concluded that as the value of BO becomes larger, the satisfaction rate drops drastically. For instance, by comparing the highest values of macMinBE and macMaxBE of scheme_7178_10 and scheme_4178_10, it is observed that when the sensors are utilising longer backoff periods that assist them to avoid the collisions, the overall satisfaction rate of scheme_7178_10 is higher than the other scheme. However, according to _7123_10 scheme, as the values of macMinBE and macMaxBE become smaller, the channel will be detected as the busy channel more frequently. Therefore, sensor nodes must wait longer for the next superframe to transmit their delayed data packets. This would increase the chance of discarding the data packets from the MAC buffer. Additionally, smaller values of macMinBE and macMaxBE causes to reach the macMaxBE sooner which makes the transaction unsuccessful as well. Figure 8b depicts the sensor energy consumption that mostly represents the period of time spent in the orphan state. Due to large difference of BO and SO values (BO-SO) in this group, less probability of overlapping ratio is expected. Therefore, shorter orphaning period is experienced and consequently lower energy consumption is observed.



(a) Satisfaction rate

(b) Sensor energy consumption

Figure 8. Impact of various BO/SO on BSN performance

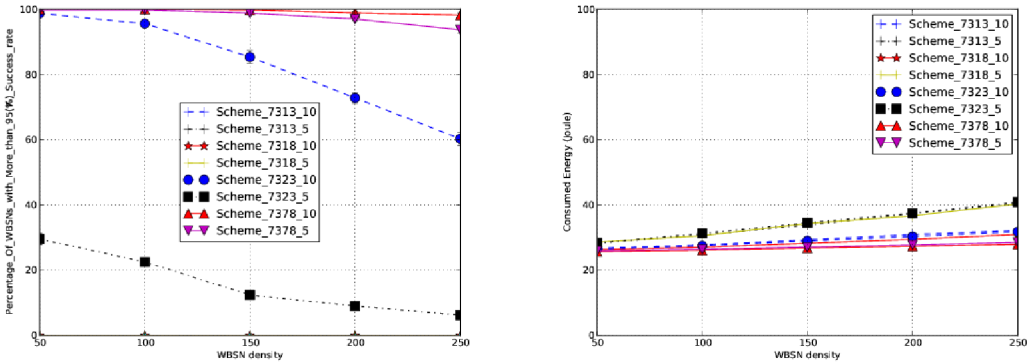
5.4. *BO = 7, SO = 3*

As the active period becomes longer, the probability of overlapping active periods will be increased. Therefore, larger values of macMinBE and macMaxBE could be the effective possible way to maintain the satisfaction rate as high as possible. Considering figures 9a, by comparing it to the corresponding figure in previous group (BO = 7, SO = 1), the impacts of both macMinBE and macMaxBE become more highlighted. Although the increase in the WBSN-density would cause higher overlapping ratio of active periods, the longer active period provides orphan sensors with the higher chance of re-associations. Figure 9b represents the energy consumption of the sensor nodes. Clearly, longer active periods results in higher probability of packet collisions and hence higher probability of unsuccessful transmission. Therefore, sensors attempt to re-transmit their data packet over and over until either the acknowledgement is received or the maximum transmission retries is reached. This results in higher energy consumption of the sensor nodes compared to the previous group (BO = 7, SO = 1).

5.5. *summary*

The followings are the concise summary of the conducted simulation study:

1) According to the attained results macMinBE and macMAxBE are the two parameters that strongly impact on WBSNs performance gains. Moreover, it is observed that both BO and SO



(a) Satisfaction rate

(b) Sensor energy consumption

Figure 9. Impact of various BO/SO on BSN performance

have the second degree of impact on WBSNs. Finally, data generation ratio caused the least impact on WBSNs performance. Please note that the selected values of data generation ratios (which has been decoupled from the BO value) have resulted in the least impact on WBSNs performance and considering other values for data generation ratio might turn out to have stronger or weaker impacts on WBSNs performance.

2) As the WBSN-density becomes larger, the satisfaction rate drops dramatically specially for those scenarios where the macMinBE and macMAxBE were configured using their smaller values. This is mostly due to lack of sufficient number of CCA attempts for sensor node that is about to transmit its data packets. Therefore, the smaller number of macMinBE and macMAxBE, would result in reaching the macMaxBE more frequently and hence the data packet will be discarded.

3) Larger values of macMinBE and macMAxBE have resulted in noticeably higher satisfaction rate especially for those scenarios where the difference between BO and SO values is larger. For instance, considering the satisfaction rate of both 7378_5 and 4378_5 scenarios, it is observed that when the difference between the values of BO and SO becomes larger, with the same macMinBE and macMAxBE, higher satisfaction rate is experienced. This is due to comparatively experiencing less overlapping ratio.

4) According to the 7323_5 and 4325_5 scenarios, the decrease in macMinBE and macMAxBE values has resulted in significant drop of satisfaction rate trend for 7323_5. Please note that if the sensor node was not able to transmit the generated data packet within the current superframe, it has to wait for the next BI to send the data packet to the coordinator. Therefore, the transmission failure occurs more frequently in scenarios with smaller values of macMinBE and macMAxBE, while the sensor is waiting for the next BI to transmit the data packet.

5) Higher data packet generation ratio results in experiencing higher collisions and consequently lower success rate.

6) The attained results of the second contribution of this survey determined the worst case scenario where particular combination of MAC parameter values has resulted in the lowest satisfaction rate and the considered simulation scenario is preferably called the worst case scenario. Overall, it is recommended to configure larger values for macMinBE and macMaxBE in the densely-populated sensor networks. This would result in longer back off period for sensor nodes and eventually less packet collisions. However, when sensor network is not densely-populated, larger values of macMinBE and macMaxBE are not positively effective for real-time applications. This is mainly due to experiencing more delay for the data packets to be transmitted to the coordinator.

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6. CONCLUSION AND FUTURE WORK

According to the first part of this paper, the performance of WSN/WBSN is reviewed in terms of varying set of system parameters. By looking at the existing state of art, it is observed that different values of system parameters would result in the diverse range of WBN/WBSN performance gains. Therefore, setting the proper value for a particular system parameter could play a key role in experiencing higher or lower performance gains. Several approaches are proposed to mitigate the negative impacts of internal interference on WSN/WBSN performance gains. However, there is a strong correlation between the internal interference and the MAC parameter values. Therefore, The second part of this paper, shows a simulation study on the impacts of a set of MAC parameters on the WBSN performance gains. More specifically, we have considered the maximum and minimum values for each and every MAC and Application layer parameters in the candidate set. Then the influence of all the possible combinations between these values on WBSNs performance gains in the presence of intensifying internal interference were explored. It is revealed that the different combinations would result in experiencing various performance gains.

The followings could be the future potential research topics: According to the so far published state of art, the impact of other system parameters are not cohesively investigated. It would be extremely helpful to know the impact of various system parameters on WBSN performance gains. Actively changing the values of system parameters could effectively improve the performance gains of WBSNs. Additionally, The amount of scrutinised and carefully conducted research on internal interference, accompanied with methods to mitigate its destructive impacts on WBSN performance gains are the other challenges that need to be investigated as future researches in the field of sensor networks.

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