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Performance of Wireless Sensor Network Medium Access Control for Monitoring

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LIST OF PUBLICATIONS

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[1]. Ameera S. Alharthi, Abdellatif I. Moustafa and Ahmed A. Morgan. **"Bandwidth-Oriented Allocation of GTS Slots for IEEE802.15.4"** *The 8th International Conference on Computer Engineering and Mathematical Sciences (ICCEMS 2019) 26th-27th December, Langkawi, Malaysia, 2019*

[2]. Ameera S. Alharthi, Abdellatif I. Moustafa and Majed M. Alotaibi. "An enhancements on IEEE802.15.4 Protocol's sleeping schedule with B-MAC integration" The 8th International Conference on Computer Engineering and Mathematical Sciences (ICCEMS 2019) 26th-27th December, Langkawi, Malaysia, 2019

Abstract

Recently, applications requirements are growing at a rapid rate. They are constantly being developed, altered, and improved upon. Achievement of these applications requirements depends on the design of the protocols of Medium Access Control (MAC) layer. Therefore, one of these reliable protocols is IEEE802.15.4 beacon-enabled mode that is considered as a de facto protocol, and it is widely implemented in the monitoring field. The protocol is designed to Low-Rate Wireless Personal Area Networks (LR-WPANs) with limited power. In addition, IEEE802.15.4 MAC uses a superframe that is divided into two periods, Contention Access Period (CAP) and Contention Free Period (CFP). Generally, within the monitoring field, the exchange of sensitive data between two nodes occurs during the CFP because it offers real-time guarantees through the Guaranteed Time Slot (GTS) mechanism. However, the 802.15.4 standard has three issues. First, lack of scalability, which is caused by the maximum possible devices that the GTS can allocate which is only seven. Second, in CFP, all timeslots have fixed-length, which leads to a slot size-induced bandwidth waste problem. Third, its duty cycle is not efficient, especially under very high duty cycle. In our thesis, we have proposed an efficient GTS allocation scheme to eliminate the GTS bandwidth underutilization problem and allows to allocate more than seven devices in same superframe. Our scheme uses variable-length timeslots that are allocated to devices based on their actual bandwidth. Also, we proposed an enhanced standard protocol's sleeping schedule, aims to conserve sensor energy without compromising the low latency. The underlying idea of our scheme is based on the B-MAC duty cycle with additional modifications. The proposed schemes were evaluated through OMNet++ simulator and the results evidenced that our proposed GTS allocation schemes and sleeping schedule scheme are outperforming the IEEE 802.15.4 standard.

Keywords: Wireless personal sensor network, IEEE802.15.4, GTS, sleep cycle, Throughput.

Dedication

This thesis is dedicated to my loving parents, to all my family, and to my friend Budoor, for their great support, endless love, encouragement and sacrifices.

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

List of Equations

LIST OF ABBREVIATIONS

MAC	Medium Access Control
WSN	Wireless Sensor Network
LR-WPANs	Low-Rate Wireless Personal Area Networks
CAP	Contention Access Period
CFP	Contention Free Period
GTS	Guaranteed Time Slot
PHY	Physical Layer
BI	Beacon Interval
SD	Superframe Duration
PAN	Personal Area Network
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
FFD	Full Function Devices
RFD	Reduced Function Devices
BO	Beacon order
SO	Superframe order
IFS	Interframe Space or Spacing

Chapter 1

Introduction

1. Introduction

Wireless sensor networks (WSN) is one of the faster-growing technologies [1]. To apply efficient WSNs able to fulfil the requirements of the applications, in particular in monitoring field, it is important to correctly select the suitable wireless protocols that will support the various layers, especially the physical (PHY) and medium access control (MAC) layer. There are popular and commercially available wireless protocols, designed for PHY and MAC layer provide various use-cases. Most of us are very familiar with the IEEE802.11protocols (WiFi), which becomes an integral part of day-to-day life. In fact, in the monitoring applications requiring of extremely low power consumption as well as low data rate wireless sensing over short distances, WiFi and similar protocols like Bluetooth (defined by the IEEE 802.15) are inappropriate: they are support high-data-rate, consume more energy, and required high-complexity network [2]. For this purpose, the Institute of Electrical and Electronics Engineers (IEEE) approved IEEE 802.15.4 standard [3] as a communication standard for Low Rate Wireless Local Area Networks (LR-WPANs). Notable, although IEEE802.15.4 protocol appears to have promising medium access control (MAC) layer and physical layer (PHY) specifications for (LR-WPANs) networks, it's still facing many challenges.

In this chapter, the basic main reasons for conducting this research are explained. First, we start with a more detailed description of the concept of wireless sensor networks including their main system properties, applications, and major challenges occur in WSN. Then, we will provide the brief introduction of the different MAC layer protocols assigned to monitoring field. Next, the “problem statement and motivation” is presented to point out the important shortcomings of IEEE802.15.4 standard protocol followed by a summary of our contributes to addressing these shortcomings. Finally, we explain the content and structure of our thesis.

1.1. Wireless Sensors Networks (WSN):

Recently, Wireless Sensor Networks (WSNs) have seen an explosion of research studies and undergo intensive research to overcome its complexity and constraint challenges. A typical WSN has consisted of a group of spatially dispersed and dedicated low-cost sensors over a limited or unlimited region in the environment for monitoring physical phenomena and capture of information of the environment and transmitting the collected data to a central sink. Each sensor comprises four basic components, sensing unit, processing unit, power unit and transceiver units [4]. Also, the tasks of each sensor node might vary relying on its type, assumed functions and the protocols to be followed.

More recently, economical sensors networked together are used for a wide variety of applications, for example, military [2, 5], environmental monitoring [2, 6], Smarthome [2, 7], health monitoring by using wireless Body Sensor Networks (BWSN) [8]. In case, monitoring field, a WSN deployed randomly or deterministically around a base station in virtually any environment to collect sample signals can provide professionals with the opportunity to remotely monitor the physical phenomenon such as a field of war and volcanic surface or attached to animals to monitor their movement. WSN appropriate for any environment even those where wired connections are impossible, where the terrain is rugged, or where physical placement is difficult. There are two WSNs monitoring methods: a regular continuous method and an event-driven method. During the regular continuous method, the sensor node transmits data periodically to the sink or shall first collect all data and transmit to sink on request. this method appropriate to applications that require a regular or continuous report of the event. whereas in an event-driven method, sensors transmit critical-event messages to the sink based on the occurrence of the target event. When a WSN is deployed, it is quite important for establishing communication links between nodes since of sensor nodes are spatially distributed autonomous in WSN. For this reason, the medium access control (MAC) protocols play an important role to construct the sensor network infrastructure in addition to control access to a shared communication medium in a fair and efficient manner. The particular characteristics of WSNs represent the main requirements of a MAC protocol running in such an environment [9]. A good design of the MAC protocol is necessary for significantly improves performance and prolong the lifetime of the network.

The following factors must be taken into consideration for the MAC protocols design:

- Energy Efficiency

  Is typically the primary goal in WSN because the network's lifetime depends on the limited energy resources of each node. In fact, the individual sensor has a small, nonrenewable energy supply and are generally deployed in a hostile environment [9].

- Scalability

  Is the property of a protocol which able to handle a growing number of nodes, traffic load, and frequency of network change by adding new nodes to the system.

- Latency

  The latency which is also known as an end-to-end delay. This feature is usually application dependent, thus in some cases, some latency delay can be tolerated. Some MAC protocols proposing solutions to minimize the latency by an optimal trade-off between factors which affected latency (energy efficiency and throughput).

- Bandwidth utilization

  Optimal utilization of the available bandwidth directly impacts the average of the network load and minimizing the delay.

- Robustness includes some characteristics such as reliability, usability, and fault tolerance. Also, robustness refers to the network ability to address and withstand failures or attacks.

The next subsection is intended to provide a general survey of the different types of MAC protocols in detail.

1.2. WSN medium access control (MAC) protocols:

In the past few years, a wide range of researchers proposed MAC layer protocols. Which can be classified into contention-based, scheduled, and hybrid protocols based on the mechanism used to dictate the access to the channel of communications.

In Schedule-Based Protocols (or Reservation-Based, as sometimes called) it is suitable for centralized topologies, in which a central unit arrange transmission. Where the available bandwidth of the link is shared in time, frequency or code, among different nodes. key features of this scheduling approach are guarantee fairness among nodes, energy-conserving and decrease data frame collisions by avoiding transmit data at the same time. Whereas the main drawback with this approach lies in achieving synchronization and require previous knowledge of network topology between the different nodes.

The Contention-Based Protocols, the nodes that have data to send make a decision on whether or not to send based on the state of medium (idle or busy). Three features give this method its name. First, synchronization nor network topology knowledge is not mandatory. Second, no conditions or role determine which nodes should send next. Third, scaling up to hundreds of nodes to be used with sensor applications. Whereas the drawback is a possibility for data collision occurs which lead to less utilization of channel because of the contention-based nature of the medium [10]. Examples involve Aloha, SAloha, carrier sense multiple access (CSMA), and others.

Hybrid MAC protocols are intended to design an efficient MAC protocol by merging the advantages of contention and schedule based schemes and attempt to avoid their disadvantages. Hybrid protocols considered random-based protocols as default transmission mode. At the same time, it works together with scheduled-based (contention-free) transmission mode when a collision detected. In other words, if collision probability increases the protocol is work with scheduled-based (contention-free) transmission. Example include IEEE 802.15.4, wireless sensor MAC (Wise MAC), and Z-MAC [11]. The major advantage of these protocols comes from its simple implementation, fast adaptability to data traffic and reduce energy consumption.

In the Chapter 2, we will review the important MAC protocols in contention-based, scheduled-based, and hybrid, respectively which have associated with the areas of environmental monitoring.

1.3. Problem Statement and Motivation

As discussed above, the IEEE 802.15.4 standard describes a Low-Rate Wireless Personal Area Network (LR-WPAN) and it is meaningful to implement this protocol in environment monitoring applications. This standard has become a leading solution for a low-data rate with inexpensive sensors that have multi-month or multi-year battery life in low-complexity networks. This increased use of the IEEE 80215.4 protocol has largely been due to the commercial availability of low-data rate, as well as the energy-efficient.

IEEE 802.15.4 MAC sub-layer supports two modes of operation either beacon-enabled or non-beacon-enabled, will be discussed in detail in Chapter 2. The IEEE802.15.4 beacon-enabled mode uses a time structure called the superframe. It consists of two sections: active and optional inactive sections. The active section comprises three periods: beacon, Contention Access Period (CAP) followed by Contention Free Period (CFP). The IEEE802.15.4 protocol uses a contention scheme by CSMA/CA in the CAP and an explicit reservation scheme in CFP. Since delay-sensitive applications mostly deal with real-time data, sometimes losing packet or receiving it with long delay could cost an environmental disaster.

The special characteristic distinguishes IEEEb802.15.4 protocol is this support quality-of-service by providing real-time guarantees through using guaranteed time slots (GTS) mechanism, this feature is quite attractive for low latency applications.

Although the IEEE802.15.4 beacon-enabled mode provides real-time guarantees in CFP, has two main limitations: 1) lack of scalability, as it is allocating GTS slots for only seven devices in the same superframe; 2) all timeslots in CFP have fixed length, which is causing the severe bandwidth wastage. The reason behind bandwidth under-utilization is a device uses only a small portion from its allocated slots, thus creates an empty hole in the CFP. This problem is quite similar to those addressed by researchers in the memory fragmentation problem in operating systems. Due to these limitations, the standard protocol may not satisfy the sensitive real-time application requirements and minimize the GTS utilization efficiency.

Another critical constraint of the IEEE802.15.4 beacon-enabled, it is using the fixed-sleep duty cycle to conserve of the sensor node's energy through enabling its inactive period. A fixed duty cycle may perform relatively limited performance in high load situations and require a trade-off between energy and latency. Notable, sensors only used batteries with an upper-bounded lifetime as their source of energy. The reasons behind energy consumption are overhearing, idle listening, control packet overhead and packet collisions caused by interference [26]. In addition, Collision occurrence requires data packet re-transmissions, which means to consume additional energy.

1.4. Summary of Main Contributions

The main contributions of this work can be summarized as follows:

1. Propose Bandwidth-Oriented Allocation of GTS Slots scheme for IEEE802.15.4-based star topology. The targets of our proposed scheme are:

  - Improving the protocol scalability, by accommodating the maximum number of GTS requesting devices in the network.
  - Utilizing the bandwidth of GTS slot efficiently, achieved by using variable slot size which is calculated according to the requesting device data packet length.
2. Propose enhancement on IEEE802.15.4 Protocol’s sleeping schedule with B-MAC integration for IEEE802.15.4-based star topology. We summarize the main targets of this algorithm as follows:
   - Achieving more energy efficiency by allowing for devices awake only in some cases, therefore, they avoid idle listening, overhearing and collision which known to cause energy consumption.
   - Scheduling sleep/wake for each device dynamically, which can be adjusted based on devices status and beacon information.
3. Construct a simulation model for each contribution separately and evaluate its own performance in various terms.

The final simulation results indicate that Bandwidth-Oriented Allocation of GTS Slots for IEEE802.15.4 scheme overcome IEEE802.15.4 standard in terms of the number of devices which can be allocated in GTS and throughput.

In addition, an enhancement on IEEE802.15.4 Protocol’s sleeping schedule with B-MAC integration also overcome IEEE802.15.4 standard in terms of Interference computation count, throughput and residual energy capacity.

1.5. Thesis Layout

The remainder of the thesis is structured as follows: In Chapter 2, we provide background and overview of the IEEE802.15.4 standard architecture and its specification. followed by reviewing the relevant literature relating to slot size-induced bandwidth waste and sleeping schedule problems, respectively. In Chapter 3, we explain the standard GTS allocation scheme and our proposed GTS allocation scheme to address standard GTS allocation shortcomings in detail. In Chapter 4, we present the shortcomings of standard sleep schedule. Followed by our proposed sleep schedule to enhancement the duty cycle of the protocol standard. Chapter 5 present our experimental simulation model mainly including simulation scenarios, Our proposed models and performance results of our proposed schemes. Finally, sections 6 and 7 present the conclusions and future works, receptively.

Chapter 2

Background and Related Work

2. Background and Related Work

In this chapter, we give a summary and comparison of the MAC protocols based on channel reservation method. Moreover, the specification of the IEEE802.15.4 standard is explained in detail in this chapter. Also, the related literature review is discussed which included two subsections: 1) improve the GTS slot bandwidth utilization; 2) sleeping schedule algorithms.

2.1. Channel Reservation MAC Protocols:

2.1.1. Contention-based MAC protocols

Contention-based MAC protocols have some features e.g. simple infrastructure, scalability probability and adaptability to network topology modifications without synchronization requirement. These protocols can be classified into two types: synchronous and asynchronous duty-cycled MAC protocols.

The synchronous duty cycling MAC protocols proposed to conserve more energy by synchronizing sleep and wake-up schedules among sensor nodes, for examples Sensor-MAC (S-MAC), Timeout-MAC (T-MAC), NanoMAC, Dynamic Sensor-MAC (DSMAC) and Utilization-based MAC(U-MAC). Whereas asynchronous duty cycling MAC protocols using a Wake-up Beacon (WB) or preamble rather than synchronizing schedules to schedule a time with other nodes and exchange the packets. A famous example of an asynchronous protocol is Sift, Alert MAC**,** ALOHA with preamble sampling and Berkeley MAC (BMAC). All the protocols mentioned above will be described in detail.

- ***Synchronous duty-cycle MAC protocols***
    - *Sensor-MAC (S-MAC)*

Produced by 802.11, SMAC is an energy efficient RTS-CTS protocol designed for WSNs. The basic idea behind the Sensor-MAC (S-MAC) is locally managed synchronizations and periodic sleep-listen schedules. Nodes work together with a fixed duty cycle approach, where turn off their transceivers in sleep period to preserve energy and turn it on an active period to exchange data frame with central sink or neighbour nodes. In addition, it is considered RTS and CTS as a contention mechanism to hidden terminal avoidance. Each node has a table that stores schedules of all its neighbours to synchronize and packet transmission among nodes. One of the key features of S-MAC is to reduce energy consumption and support self-configuration whereas, it doesn't achieve simple implementation, scalability, and tolerance to varying network cases [12]. In S-MAC, when a node has more data to send, it monopolizes the channel medium that leads to unfair for other nodes that have short packets.

In addition, S-MAC suffer from rigidity: as nodes have not capable to dynamically set their sleep/wakeup schedules to adapt to changes in traffic loads. Also, high latency still occurs caused by sleep delay. To overcome this problem the T-MAC and nano-MAC proposed based on the S-MAC protocol.

- *Timeout-MAC (T-MAC)*

Timeout-MAC [10] solve SMAC's inflexibility by suggested an adaptive duty cycle in which set the duration of both active periods and sleep period in conformity with varies the traffic. Where each node ensures that the minimum duration of the active period most equal or exceeds the maximum contention duration and the RTS/CTS transmission. Whereas the nodes turn off its transceivers in case it does not hear anything within the period and does not expect any traffic. The feature of the T-MAC is to save energy more than S-MAC whereas the drawbacks of T-MAC is the same as S-MAC it represents in complexity, scaling problems and increases delay.

moreover, minimize the duration of the active period leads to reduce the throughput, ability to detect surrounding traffic and adapt to varying network cases. Figure 1 shows the difference between S-MAC and T-MAC protocols.

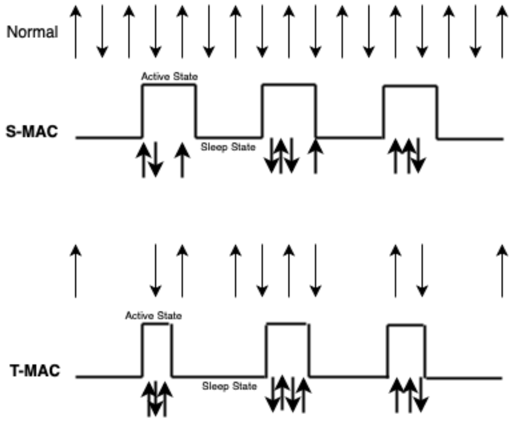

Figure 1: Comparison of the active state between S-MAC and T-MAC

- *NanoMAC*

The nanoMAC aims to make improvement on S-MAC by reducing power consumption during high traffic [10, 13]. It is considered as p-non-persistent CSMA/CA MAC protocol. The RTS-CTS-nDATA-ACK handshake represented operation cycle. Where RTS/CTS included IEEE-addresses of the sender and receiver nodes for avoiding extra control overhead for the data frame, information about sleep time and the number of packets to be transmitted. After RTS/CTS exchange, nodes may transmit one or more than one data frame and receive single ACK frame confirmation. where the sender needs to resend the corrupted frames at a later time.

The main features provided by nanoMAC is an expert sleep algorithm, which aims to reduce both power consumption and idle listening time. The algorithm classified sleep time into four groups based on the traffic density and application requirements, where the assignment of the sleep groups governed by the application layer. Sleep Group 0, known as an always-on mode. Where the nodes turn off their transceivers if it detects contention on the access medium or to prevent idle overhearing. Each node can knowns the duration of channel occupation through the information carried on RTS/CTS. Operating on this group may achieve the highest throughput and lowest end-to-end delay. Whereas sleep in group 1,2 and 3 is followed to duty cycles. Where each node has a very small and fixed awake duration based on its group where it can communicate with its neighbours. When the node has a packet to send it shall extend its wake duration until finish transmitting or receiving the packets then immediately turn off its transceivers. NanoMAC also used additional control packet called broadcast RTS (BRTS) frame, it special to nodes have broadcast message where shall transmit BPTS before deciding to transmit a broadcast message. On receipt BPTS, each node extent its active period to receive a broadcast message [13].

In consequence, NanoMAC minimizing idle listening and overhearing by sophisticated sleep algorithm, thus that achieves low energy consumption.

- *Dynamic Sensor-MAC (DSMAC)*

Dynamic Sensor-MAC [10] it is an expanded version of S-MAC, it proposed to reduce latency under high-traffic conditions in sensitive applications. Each node adding extra active periods to increases its duty cycle to meet the low latency or high traffic requirement. When nodes are intent to adding extra active periods, it broadcast a SYNC packet to its neighbors to notify them about its additional active schedule. On receipt the SYNC packet, neighbor make a decision whether to increase its duty cycle to satisfy the received schedule or not. Observe, nodes can decrease their duty-cycles by removing the added active periods in order to achieve more reduce power consumption.

- *Utilization-based MAC (U-MAC)*

U-MAC [10, 14] make a significant improvement in S-MAC to reduce end to end delay in three aspects:

first, various duty cycles, where does not determine the same duty cycle for nodes, and each node can be work with special periodically listen and sleep schedules. Second, utilization-based tuning of duty-cycle. Each node tuning its duty cycle based on variation traffic loads of every node in a network. Such variation satisfies the diversity of conducted functionality by a particular node and its location in the network. The utilization function defined as the attribution of the actual transmissions and receptions executed by the node over the whole active period. If the utilization function is low, then the node faces a long idle period within the active period. Third, selective sleeping after transmission. This improvement leads to prevents energy wastage. The "selective" means, each node shall check after finishing each transmission if it is at scheduled sleep time or not and turn off its transceiver if it's at scheduled sleep time. U-MAC's essential idea is similar to T-MAC's, they participate in the drawbacks.

Actually, the synchronize-duty-cycled protocols offering good performance with one-hop networks, in contrast, they achieve worst performance when working with multi-hop networks because of high delay and hidden terminal problem.

- ***Asynchronous duty-cycle MAC protocols***
  - *Sift MAC protocol*

Sift [10, 15] protocol is a randomized CSMA MAC protocol with fixed-size contention window. It is suitable to handle a large number of sensors for event-driven wireless sensor networks. The essential idea of Sift is Instead of using varying the contention window size as many MAC protocols based on CSMA, it works with fixed-size contention window where the transmission slot picked based on non-uniform geometrically increasing probability distribution. Which may reduce the latency for the receipt of the event message [15]. Listening to all nodes before sending leads to increased overhearing and idle listening, which represents the main drawbacks of Sift protocol.

Sift protocol has the following two main features in addition to the adaptive to change: very low latency and maintains good channel utilization. whereas the drawbacks are increased idle listening and overhearing.

- *Alert MAC*

The main idea of Alert MAC protocol [16] the receiver node collect the event-driven reports from the sensing nodes and divided time into Alert slot. Where each Alert slot sufficient to send a single packet and receive its acknowledgment. Each time slot contains multiple frequency channels with varying priorities used by the sender and receiver.

This technique proposed to reduce collision and interference among nodes. Also, it is non-carrier sense protocol, therefore, it is suitable to solve the hidden terminal problem. Whereas the main drawback of the protocol is the throughput is heavily affected by the traffic pattern.

- *ALOHA with preamble sampling*

ALOHA with preamble sampling is low power technique for sporadic communications in an Ad Hoc wireless network. The major idea for this protocol approves nodes to turn off its transceivers (sleep mode) for most of the time when it detects the access medium is idle, otherwise, it awakes and listen until receiving the packet [17]. When a node has a packet to send, it transmits its packet randomly as a similar way in ALOHA but with long preambles to correspond the channel listen period.

A unique feature of this protocol provides energy efficient operation in constant monitoring WSNs in case low traffic. Whereas the main drawback is a higher probability of collision as a result of utilizing the sensing preamble which leads to expanded transmission and reception duration. To overcome this problem, each node shall use the long preamble only for first frames in order to provide time synchronization among nodes.

- *Berkley Media Access Control (BMAC)*

B-MAC is an adaptive preamble sampling protocol called low power listening (LPL) to reduce duty cycle and minimize idle listening, which means it performs listen to the medium at a fixed time interval for some action [18]. We will describe the B-MAC duty cycle in Chapter 4 when we study detailed our second scheme design. The most prominent distinguishing characteristics additional to no synchronization is needed are more simplicity of design and implementation where does not require additional control packets such as RST/CTS or SYNC packet, scalability and energy efficiency operation. Whereas, the main drawback is a large overhead caused by the long preamble.

2.1.2. Schedule-based MAC protocols

In a schedule-based MAC protocol, TDMA is considered a basic technique for most of the protocols used in sensor networks for environmental monitoring applications [16]. TDMA has some features such as reduce energy consumption by avoiding useless idle listening or over-hearing and minimize collision probability.

TDMA technique divides the channel times into many time slots. Each slot has been allocated to single nodes for exclusive use, thus the node shall wake and send its packet only in their allocated slots and remain in sleep mode at other slot times. In TDMA the time synchronization is implemented, which can be defined as each node must know precisely the time that node starts transmission its packet in its allocated slot.

Time synchronization considered an important critical to guarantee the communication secure, reliable and conflict-free. In the same time, it is also represented as one of the limitations and challenges since any varying clock drift or uncommitted synchronization results in a serious problem.

In addition, the various structural changes that occur on nodes such as mobility, redeployment and death node affect the network robustness and make the TDMA not scalable or adaptive protocols. Also, delays can occur in a network for various reasons: unused time slot, packet corruption and a packet which require retransmission. For the intrinsically advantage of energy conserving TDMA protocols have been recently attracted great attention for many applications requires clusters network topology.

In cluster-based TDMA protocol, sensor nodes orderly distribution or arrangement into many clusters, where each cluster heads are responsible for coordinate scheduling slots of time their members in a TDMA approach. All communication occurs only between a coordinator and its members, then the coordinator collects and compress all data from the nodes and finalizes the task by redirects the collected and accumulated data to the base station. We discuss some

TDMA-based protocols that do explicitly address monitoring applications such as Low Energy Adaptive Clustering Hierarchy (LEACH), Distributed energy aware MAC (DEMAC) protocol, Power Aware Cluster TDMA (PACT) protocol and Bit-map-assisted (BMA).

- ***Low Energy Adaptive Clustering Hierarchy (LEACH)***

The LEACH considers as cluster-head rotates, which consist of two phases. First called setup phase and second is steady-state phase. In the first phase, one node assigned as cluster-head and organize other nodes into clusters. After the setup phase, the cluster headsets up TDMA schedules for all members nodes in its group. Thus, it collects reports from its members and forwards collected data to the base station [19].

Although this protocol achieves lower energy consumption and creates or maintain clusters for the purpose of improving the lifetime of a wireless sensor network, it has disadvantages such as ignoring the residual energy level of the nodes and the distance between the base station and cluster head.

- ***Distributed Energy-Aware MAC Protocol (DE-MAC):***

DE-MAC [20], the distributed energy-aware MAC protocol is based on TDMA and hence it achieves avoiding additional energy consumption.

It was designed to overcome LEACH drawback where handle and considers the residual energy for each node. Which give the critical nodes (i.e., current energy level is below a threshold value) higher priority to sleep more than their neighbor nodes to achieve load balancing among all nodes.

The main feature of DE-MAC protocol minimizes the time of idling listening of critical nodes (low energy nodes). In contrast, the drawback of such a protocol is that it is more vulnerable to end-to-end delays. Due to the low energy nodes sleep for more time.

- ***Power Aware Clustered TDMA (PACT)***

The PACT protocol [21] was designed for large sensor networks and uses a passive clustering like LEACH to create a network with cluster heads and sinks for the purpose to achieve the advantage of a dense topology to extend both nodes battery and network lifetime. The function of the cluster head is assigned to the nodes which have the biggest energy level, however, is rotated as soon as energy level changes, in the interest of maintaining a minimum of energy level among sensor nodes.

PACT uses TDMA superframe which is consisting of control mini slots followed by longer data slots. Nodes only turn on their transceivers in them allocate data slots in order to save energy. The feature of this protocol it is adapting with energy consumption to user traffic. Whereas, the drawback is a large amount of overhead and idle listening is still there due to clustering.

- ***Bit-map-assisted (BMA)***

An intra-cluster communication Bit-map-assisted [22] also designed for large-scale event-driven monitoring applications. In addition, It proposed for minimizing power consumption caused by overhearing or idle listening and overcoming the end-to-end delay problem in a cluster-based TDMA MAC protocols.

For energy conservation, it follows a similar procedure as IEEE802.15.4 where during an idle period (a node has no data to send), all the source nodes and non-source nodes turn off their transceivers till the next round. Otherwise, when a node has data to send, it is following a TDMA scheme where send their data in their allocated data slots. The most significant feature of BMA-MAC is energy efficiency and maintaining low delay performance. Whereas, the drawback of this protocol is that it is only compatible with low and medium traffic load cases.

2.1.3. Hybrid MAC protocols

As is evident from the above discussion, A contention-based protocol probably acceptable as highly autonomous protocol but leads relatively energy waste as a result of collisions, overhearing, control overhead and idle listening. A contention-free” protocol overcomes many of these shortcomings and accomplishes efficient usage of energy, but it necessitates synchronization and it will be difficult to address scalability challenges. There are, however, specific applications requirements like event-driven monitoring that cannot be fully accomplished with single CSMA or TDMA alone consequently, combining the best features of both types of protocols is crucial.

Current research trends in WBAN MAC focus on designing a hybrid MAC in order to adjust the behavior of MAC protocols between CSMA and TDMA to achieve the goal of energy efficiency, scalable and adaptive to dynamic changes in the network. Typical examples of such protocols are: Zebra Media Access Control (Z-MAC); Crankshaft; IEEE802.15.4.

- ***Zebra Media Access Control (Z-MAC)***

Is one of the most important examples in hybrid scheme, which able to dynamically switch between random access and frame-based scheduling based on contention level information on the channel. It is work with CSMA at low contention case or TDMA at high contention case. At the setup phase, slot allocation is handled by DRAND (Distributed Randomized Time Slot Assignment Algorithm) protocol to assign a slot to each node. Each node must use its allocated slot for transmission. Also, if a node does not use its assigned slots or needs more than one slot, it attempts to occupy its neighbors' free slots by using CSMA [23]. Z-MAC protocol has the ability to adapt to variable traffic patterns thus it achieves high channel utilization and low latency as well as guarantee fairness. In contrast, in case high traffic patterns, Z-MAC suffers from lack of scalability when adding a new node in the network. A new node cannot transmit its data packet because there are no time slots specifically assigned for it. Another drawback of Z-MAC comes from schedule drift [10], where we should periodically rerun the DRAND Algorithm to resolve the schedule drift which leads to consuming more energy [24].

- ***Crankshaft***

Crankshaft [25] is a prominent protocol designed for Dense Wireless Sensor Networks to maximize energy efficiency. In overview, crankshaft works as follows: time is divided into frame times, each divided into slots for unicast message followed by slots for broadcast message. During a broadcast slot, every node has to be awake to listen for an incoming message. Unicast slots are owned by nodes, and two neighbors share the same slot in order to reduce complexity.

Each node can transmit at its allocated slot provided it wins the contention. Contention mechanism using a method similar to that employed by WiseMAC and SCP, which called non-persistent CSMA with a synchronized preamble.

Crankshaft protocol also employs sift technique to reduce collisions and overhearing avoidance has been handled with a slot scheduling of sensor nodes [25]. Crankshaft protocol achieves high energy efficiency and a long lifetime of the network thus, suitable for long-lived monitoring applications. The main drawback of the crankshaft protocol is that does not seem scalable, with slot allocated statically, does not take into consideration the interference and traffic variation.

- ***IEEE802.15.4***

IEEE 802.15.4 protocol designed to be used with Low-Rate Wireless Personal Area Network (LR-WPAN) and low-power sensor networks [3]. It is often referred to as ZigBee. IEEE 802.15.4 support two operation mode: beacon-enabled and non-beacon enabled mode. The beacon-enabled mode considered as hybrid MAC protocols, which uses a superframe structure including of Contention Access Period (CAP) followed by Contention Free Period (CFP). This protocol is will be the main focus of attention in this thesis and described in detail in Chapter 2. IEEE 802.15.4 achieve energy efficiency, scalability, reliability, and flexible MAC Frame Structure.

2.1.4. Summary of MAC protocols:

The previously survey describes of various MAC protocols and their features and drawbacks in the monitoring field. Based on the mechanism to access channel, these protocols broadly classified into scheduled, contention-based and hybrid protocols. As can be observed, each of these protocols uses various shared media access techniques to achieve one or more Quality of Service (QoS) requirements, such as minimizing latency, energy efficiency, scalability and so on.

Even though many MAC protocols have been proposed, there is no protocol accepted as standard. The significant reason behind this is that the choice of an appropriate MAC protocol depends on applications requirements, which means that there will be one protocol may more appropriate for certain applications than the other protocol, and vice versa. For instance, TDMA has a feature collision-free medium access in order to achieve better bandwidth utilization and an energy-efficient network. However, requiring strict synchronization, centralization, lack of scalability, a node's interference and decrease throughput at low traffic loads due to idle slots.

On the contrary, contention-based MAC protocols even though do not require nodes scheduling, it works with additional collision avoidance or collision detection algorithms to reduce the collision probability. These protocols have advantages of scalable, adaptive to the network changes, lower delay and achieve better throughput in low traffic loads.

As mentioned above, the selection of MAC protocol is application-defined, thus contention-based protocols suitable for monitoring the network with critical data and event-driven WSN applications, which means the appearance of events are unpredictable. Whereas contention-free protocols suitable for the network requiring data gathering periodically or on-demand. Also, hybrid protocols provide energy efficiency in varying traffic conditions as well as they address Quality of Service (QoS) issues such as latency, throughput, and channel utilization. Table 1 summarizes the MAC protocols designed for monitoring applications presented in this section, comparing some of their characteristics.

Table 1: Comparison between MAC protocols in monitoring field

1) |Contention-based MAC protocols						
Protocols	MAC Approach	Applications	Synch. requirement	Over-head	Strengths	Weaknesses
S-MAC	CSMA, fixed duty-cycling, virtual clusters	Event-driven, Long idle periods, light traffic load applications	Loose	RTS, CTS, ACK, SYNC	low energy consumption when traffic is low, reduces collisions caused by Hidden/ Exposed Terminals.	Rigidity, Sleep delay, idle listening and overhead still occur.
T-MAC	CSMA, Dynamic duty-cycling, virtual clusters, Future request to send	Event-driven, long idle periods, variable traffic load applications	Loose	RTS, CTS, ACK, SYNC	Adaptive active time, saves more energy than SMAC.	Early sleeping problem.
Nano-MAC	non-persistent carrier sense multiple access with collision avoidance (CSMA/CA)	Low-Power for high-density WSN.	Loose	RTS, CTS, ACK	Conserve battery energy	sleeping schedules are not as flexible as those of T-MAC, high communication latency
DSMAC / U-MAC	CSMA, dynamic duty cycle	Event-driven, high-traffic conditions in long-time monitoring applications.	Loose	RTS, CTS, ACK, SYNC	Good delay performance	energy efficiency is tradeoff with latency, high probability of collision
SIFT	CSMA/CA contention window-based	Event driven report, low latency requirement application.	NO	ACK	simplicity, low latency, channel utilization, Reducing Collisions	increases idle listening and overhearing
Alert MAC	non-CSMA	Low-Latency event-triggered urgent messages	NO	Preamble, ACK	minimizes delay, solve hidden problem, robustness	Affected by the traffic load condition.
ALOHA with preamble sampling	Aloha/CSMA	low traffic wireless sensor network applications.	NO	Preamble, ACK	energy efficiency	long preamble collision

2) Schedule-based MAC protocols						
LEACH	TDMA/clustering	periodic data collection and monitoring application	Tight	ADV, Join Req, schedule	increased throughput and network lifetime, reduce idle listening, collision and interference.	TDMA schedule introduces time delay.
DE-MAC	TDMA/ scheduling	distributed energy-aware-applications.	Tight	Vote packet, Radio-power-mode packet	energy efficiency, minimize collision	increased latency in high traffic, lack of scalability and adaptivity
PACT	TDMA/passive clustering	large-scale-wireless multi hop applications.	Tight	Control packets, ACK	Reduce overhead and prolong the network lifetime	lack of scalability and adaptivity
BMA	TDMA/E-TDMA	large scale event-driven applications	Tight	Control packets, ACK	simplicity, energy efficiency	suitable for low and medium traffic loads
3) Hybrid Protocols						
Z-MAC	CSMA/TDMA slot stealing	adaptability to the level of contention in the network	Partially Tight	Control packets, ACK	high throughput, robust to topology changes and synchronization failures	
Crankshaft	np-CSMA/ receive slot scheduling	low-energy applications under converge cast traffic pattern.	partially Tight	ACK	high delivery ratios, energy efficiency.	Collision may occur.
IEEE 802.15.4	Slotted CSMA-CA/TDMA	low data-rate and low-power consumption applications	Tight	Beacon, ACK	Very flexible MAC layer, energy efficiency, scalability.	Not suitable to heterogeneous and variable traffic since only limited number of GTS is supported.

2.2. IEEE 802.15.4 protocol Standard

As mentioned above, the IEEE802.15.4 standard has been designed to fulfil the QoS requirements of applications that transmit information over relatively short distances through devices with little to no underlying infrastructure. Specifically, the IEEE 802.15.4 protocol can provide features such as low-data rate, low-power consumption, low- cost, and low-complexity implementation.

The main identifying feature of IEEE 802.15.4 among WPANs is the importance of supporting real-time guaranteed service by operating on beacon mode and enabling its guaranteed time slot (GTS) mechanism, without sacrificing flexibility or simplicity [27, 28]. Additionally, the IEEE 802.15.4 standard defines two separate kinds of devices, namely, Full-Function Device (FFD) and Reduce-Function Device (RFD). The FFD can operate as PAN coordinator so that establishing a self-organizing wireless network, managing PAN functions and enabling beacon mechanism. By contrast, the RFD cannot able to operate as the coordinator because it designed with minimal resources and memory, intending to exploit it to reduce power consumption and increased battery life even more.

In addition, IEEE802.15.4 support two network topologies ether star or the peer-to-peer networks, as represented in Figure 2. In a star network, every device is connected to a central PAN coordinator (FFD), in which all communication controlled by the PAN. Another hand, in the peer to peer network, all devices are equal, and the communications are done directly among network devices.

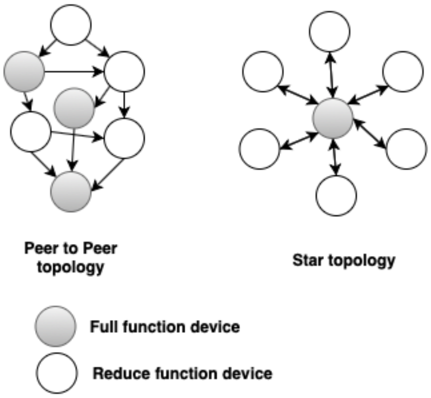

Figure 2: IEEE 802.15.4 Network topologies

IEEE 802.15.4 standard specifications intend to provide the fundamental lower network layers of a type of wireless personal area network (WPAN), where protocol only covers physical layer and medium access control -sublayer. Figure 3 shows the IEEE802.15.4 layers architecture, where each layer responsible for part of the standard, in addition to its main function as offers services to the higher layers.

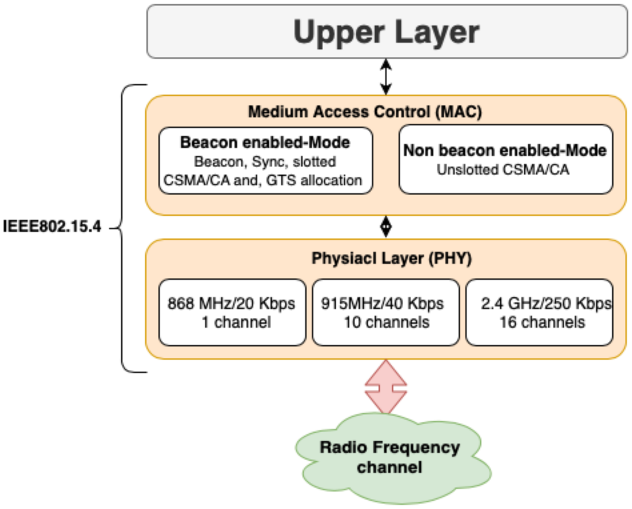

Figure 3: IEEE 802.15.4-layer architecture

For more details, the upper layer, illustrated in Figure 3, composed of the network layer and application layer, respectively. The network layer responsible for network established and packets routing, while the application layer responsible for generating packets and operate as users' interfaces. These layers definition is not considered in IEEE802.154 protocol standard. The descriptions of physical and MAC layers, with detailed information, are shown below.

1. Physical Layer

IEEE802.15.4 PHY layer support three types of frequency band 2.4GHz, 915MHz and, 868MHz. The 2.4 consider as a free band in the world, it consists of 16 channel and provides up to 250Kb/s data transmission rate [27]. Whereas 915MHz and 868MHz considered as ISM band and used mainly in some region like the United States and Europe respectively. The 915MHz consists of 10 channel and provides up to 40 kbit/s data transmission rate, while 868MHz consists of one channel and provide up to 20 Kb/s data transmission rate.

The functions of PHY in addition to frequency band selection and packets transmission or receiving, it also responsible for energy detection (DE), collision detection, Clear Channel Assessment (CCA), and etc. [3].

2. MAC sub-layer

MAC sub-layer can in effect be regarded as IEEE802.15.4 protocol standards "building blocks", which supports the two operation modes either beacon-enabled or non-beacon-enabled. In addition, the acknowledgement (ACK) is optionally used to enable reliable data transmission and reduce retransmission packets.

- ***Non-beacon-enabled***

During this mode, no beacons are broadcasts and each end-devices request its packet by non-periodic poll.request primitive. All exchange of communication frame is done by non-slotted

CSMA/CA algorithms. Generally, the non-beacon mode it considered as low-overhead, so, achieves energy-efficient and does not need synchronization as tight as a beacon-enabled mode.

- ***Beacon enabled mode***

Comparatively, the beacon-enabled mode is commonly used in WSN published studies and applications, because of two different ways for data transmission is possible either multicast during the contention access period or guaranteed time slots during the contention-free period. In the beacon-enabled mode, The PAN coordinator broadcast beacon periodically, to form superframe structure and providing synchronization among nodes. Synchronization helps devices to sleep between coordinated transmissions, to reduce the consumption of energy and prolong the network lifetime. The superframe structure defined by the PAN coordinator is shown in Figure 4.

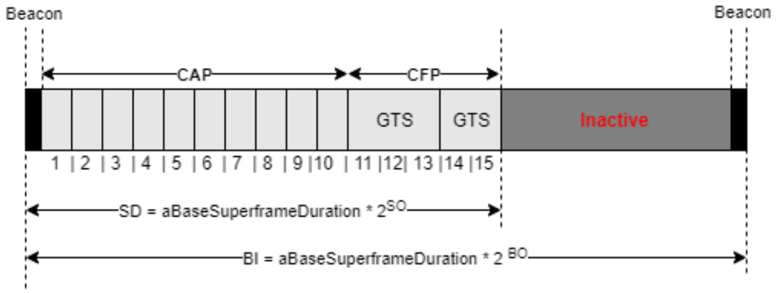

Figure 4: IEEE 802.15.4 superframe structure in the beacon-enabled mode

It may be divided into two main portions: the active portion and the inactive portion. The latter portion used to conserve energy: Each device turns OFF its transceivers until next beacon. The active portion consists of 16 timeslots and composed three main periods: two successive beacons as its limits, the contention access period (CAP), and the contention-free period (CFP). The PAN coordinator broadcasts the beacon frame at the first slot of every active portion. The beacon frame containing PAN identifier and superframe structure specification. The contention access period starts after beacon slot immediately and continues until the beginning of the CFP, if present or on a superframe slot boundary. During the CAP, exchange of transmission frames is done by CSMA/CA for all types of packets except an acknowledgement frame.

Generally, CAP suitable for sporadic and unexpected flows events. The CAP followed by CFP, which provide Guaranteed Time Slots (GTS). GTS consists of one or more contiguous time slots allocated by the PAN coordinator, the access to the shared channel is done without contention among nodes.

As illustrated in Figure 4, the length of the whole superframe structure, called Beacon Interval and its active portion, called Superframe Duration (SD) is governed by two major parameters: Superframe Order (SO) and Beacon Order (BO). The BI represents the time between two consecutive beacons and ranges from 15 ms to 245 s, can be calculated by Equation (2.1). Also, SD represents only the active portion and can be calculated by Equation (2.2).

$$BI = \frac{aBaseSuperframeDuration \times 2^{BO}}{R_S} \qquad 0 \leq BO \leq 14 \qquad (2.1)$$

$$SD = \frac{aBaseSuperframeDuration \times 2^{SO}}{R_S} \qquad 0 \leq SO \leq BO \leq 14 \qquad (2.2)$$

where according to standard definition, *aBaseSuperframeDuration* and Data Rate Symbol (R_s) are equal 960 symbols and 62,500 symbols/s, respectively. Notable, if BO = 15 the superframe shall not exist and the MAC layer operate on non-beacon-enabled mode, thus SO value is ignored.

Let denote T_{slot} as the time of one slot, can be calculated by Equation (2.3) and estimates its length from 96 ms to 15.7 sec.

$$T_{slot} = \frac{SD}{16} \qquad (2.3)$$

According to the definition of IEEE802.15.4 standard, the *aMinCAPLength* represent the smallest length that can be accepted for CAP [3], if GTS is present. *aMinCAPLength* can be calculated by Equation (2.4).

$$aMinCAPLength = SD - (7 \times T_{slot}) \tag{2.4}$$

Table 2 includes every possible length of the superframe duration and their associated lengths such as the timeslot and the minimum CAP duration based on the equations mentioned above, for different values of SO.

Table 2: The value of SD,T_{slot} and aMinCAPLegth for different value of SO

SO	SD (sec)	T_{slot} (sec)	aMinCAPLength (sec)
0	0.01536	0.00096	0.00864
1	0.03072	0.00192	0.01728
2	0.06144	0.00384	0.03456
3	0.12288	0.00768	0.06912
4	0.24576	0.01536	0.13824
5	0.49152	0.03072	0.27648
6	0.98304	0.06144	0.55296
7	1.96608	0.12288	1.10592
8	3.93216	0.24576	2.21184
9	7.86432	0.49152	4.42368
10	15.72864	0.98304	8.84736
11	31.45728	1.96608	17.69472
12	62.91456	3.93216	35.38944
13	125.82912	7.86432	70.77888
14	251.65824	15.72864	141.55776

2.3. Literature review

Despite IEEE 802.15.4 has fascinated both the research and development communities, remarkably few studies have been designed to address bandwidth underutilization of CFP and propose an efficient duty cycle.

In order to overcome the shortcoming of standard in term of GTS bandwidth utilization and enable more than seven devices to utilize the GTS in the same superframe, Bhosale and Ladhe presented a survey on many improved methods [29]. Although studies have been conducted by many authors, handling of slot size-induced bandwidth waste problem by reducing the slot time is still insufficiently solved. For instance, in [30] proposed the revised scheme, where dividing the CFP into 16 smaller timeslots with fixed-length rather than using the same length of the slot in CAP. This scheme improves bandwidth utilization and allows more than seven devices to owns GTS slot at same superframe. The same slot splitting idea was extended by [31], the author proposed a new scheme in which each GTS slot split to half of the GTS length in the standard. The author also proposed an additional scheme aimed to fairness allocation of GTS slot by allowing for many nodes to share GTS slot. The later scheme appropriates with the events prepared at periodic intervals. The authors [32] also following the slot splitting approach, they split every single slot into a number of tiny slots, where the number of tiny slots equals the value of the superframe order. For instance, if SO= 14, each GTS slot will split into 14 tiny slots, meaning that total tiny GTS slots for this scheme would be 7×14=98 tiny GTS slots.

Overall, even though the aforementioned schemes and similar ones, utilize small equal duration of GTSs played a critical role for reducing the slot size-induced bandwidth waste problem, these schemes may not completely eliminate the possibility of bandwidth waste. Also, The earlier schemes allow to more 7 devices reserve allocated GTSs at the same superframe, but the possible number of devices is still limited and they may not serve the maximum of the associated devices.

Similar to the techniques mentioned earlier, [33] also try to address the bandwidth under-utilization problem through Indirect modification for the slot duration. They proposed a method to divide each superframe into two smaller superframes, each single divided superframe can be further subdivided into smaller ones. Division process led to minimizing the whole duration of the superframe, consequently minimize the GTS slot size. However, although this proposed can achieve high performance, the minimizing of the waste bandwidth problem is still not enough, in addition to it consume more energy. The authors [34] proposed new techniques aimed to reduce network latency by handling with small MAC frame equal to LIFS (*aMaxSIFSFrameSize*) and remove the inactive portion in the beacon interval. Also, they adjusted the length of the GTS slot in fixed-length based on the length of packet size, which means the length of each GTS slot also equals LIFS = 18 bytes.

The results of these techniques evidence that significant performance increased by reducing the bandwidth under-utilization problem and allowing the maximum number of associated devices to reserve GTSs. The main shortcoming is the proposed techniques are only applicable to a small MAC frame does not exceed 18 bytes, as suitable for light traffic load.

The following studies deserve mentioned because it proposed a new concept to adjust the GTS slots based on the actual data length. For instance, both i-GAME [35] and SUDAS [36], proposed algorithms to adjust the duration of GTS based on the actual data frame length and the packet arrival rate.

In fact, adjusting the GTS slot length using these two algorithms requires detailed information from GTS requesting devices about their transmission requirements such as the actual length of a data frame and the average arrival rate. Hence, although these algorithms and like ones, optimize whole network performance, they seem limited effectiveness because these algorithms used constant duration for all GTS slots and may not allocate the maximum number of devices requesting GTS.

In our thesis, we follow the last approach in adjusting the duration of GTS time slots based on the traffic characteristics of the requesting devices, since we propose a new algorithm allows the varying duration of GTS from one timeslot to another at same superframe through determining precisely for the data frame length, in addition, it allocate GTS slots for the maximum possible number of devices.

Energy-efficiency is another key requirement in IEEE802.15.4 protocol, so recently, more effort has been dedicated to improving the efficiency of the protocol energy in WPAN. In fact, the BO and SO parameters are governing the protocol duty cycle; therefore, most of the studies propose methods to manipulate these parameters values to achieve an efficient duty cycle. These proposed methods have three possible cases: either PAN coordinator modifying both of the BO and SO values according to the node's remaining battery capacity, modifying its SO value whereas its BO is fixed, or else the opposite case, where modifying its BO value while its SO is a fixed value.

For example, [37] proposed an algorithm called the Adaptive Beacon Enabled Mode (ABEM), allows PAN coordinator to adaptive its duty cycle (modify its BO and SO value) according to node`s battery capacity. The PAN coordinator gets information about nodes battery capacity through previously report sent by nodes. Although this algorithm achieves energy-efficiency, it required additional frames and procedures.

Some studies have shown a dynamic duty cycle, for example: [38] proposed a different algorithm to adapt the duty cycle with respect to the traffic load called AMPE. By this algorithm, the PAN coordinator fixing BO to a maximum value while adapting its SO value depends on the occupied proportion of the superframe. In order to select an optimal value to SO, the PAN coordinator first measure the superframe occupation rate and compares it with upper and lower thresholds. If the measured rate is greater than the upper threshold, the coordinator increases active period by increases SO value. Otherwise, decreases SO value, which means the length of the active portion is reduced. this algorithm highly recommended for the star network although does not consider CFP and suffer from more overhead.

similarly, [39] proposed the dynamic super-frame adjustment algorithm (DSAA) based on superframe occupation rate and collision ratio. It also adjusts only the SD length by adapting SO value whereas BO value is fixed. This algorithm works as follows: the PAN coordinator calculates the superframe occupation rate, collision rate and two thresholds at the end of each superframe. The two thresholds can be defined as the accepted maximum and the minimum limitations of occupation and collision ratio, respectively. Based on PAN calculations this algorithm decides either to increase or decrease the SO value. This algorithm conserves more energy and optimizes channel utilization whereas the main drawback is increased packet latency.

Similar the two aforementioned works above, Adaptive Duty Cycle Algorithm (ADCA) [39] controlling active portion by modifying the SO whereas BO is fixed. This algorithm makes its decision based on the superframe idle time, throughput and queue state of nodes. Relying on these factors especially the idle time the proposed algorithm decides either to increase or decrease the SO value. In case the idle time greater than half of the CAP, the SO value is decreased for the next super-frame. In case the idle time less than half of the CAP, the PAN coordinator makes a comparison between the number of received packets and the number of pending packets then if the pending packets are greatest, it increases BO value for the next BI. Although the algorithm show improvement in energy-efficiency, it increases the complexity of the network, especially when the network is large.

An Adaptive algorithm to optimize the dynamics (AAOD) [40] is also intended to dynamically adjust the active portion, means modify only the SO value. This algorithm provides flexibility to accommodate network heterogeneity and achieve increasing packet delivery ratio. AAOD is a simple algorithm, it adapts duty cycle based on the comparison between currently received packets and packet received in the previous superframe. In case the number of currently received packets is increased, the PAN increases SO value and vice versa.

Differently from the above studies, the authors [41] proposed a hierarchical addressing algorithm, which allows to each node perform a speculative selection of the next coordinator based on a $LQIthreshol$ value.

As summary of algorithms mentioned above, they are changing either SO or BO values or both, they may achieve high throughput, low-latency, and prolong network life, when utilizing optimal BO and SO values. In fact, the over an increase in SO required in high traffic load may be led to consuming more energy. In contrast, a low value of SO means reducing active portion, therefore, lowers the duty cycle, means all nodes may spend most of their time in a sleep mode. Low duty-cycle caused inefficient performance, high-latency and high collision rate as a result of the little access opportunity on the channel. Notably, all these algorithms required that BO > SO thus the inactive period is present. In this thesis, we proposed a duty cycle algorithm similar to B-MAC duty cycle with considering BO value equals SO, means ignoring the inactive period in order to reduce latency.

Chapter 3

Bandwidth-Oriented Allocation of GTS Slot

3. Bandwidth-Oriented Allocation of GTS slot

In this chapter, we considered the first part of our thesis schemes: Bandwidth-Oriented Allocation of GTS Slots for IEEE802.15.4 is described in detail. The section also describes the analysis of the standard GTS, followed by a detailed explanation of the proposed scheme.

3.1. Standard GTS Analysis

As previously mentioned in chapter 2, when the MAC sub-layer operates in beacon-enabled mode, a superframe will be divided into two parts i.e., the CAP and CFP. Generally, within the monitoring field, the exchange of sensitive data between any two nodes occurs during the CFP, because it provides real-time assurance through the Guaranteed Time Slot (GTS) mechanism. According to the standard, we can define the GTS as the contiguous fixed-length slots that require the previous allocation. Where the maximum number of GTSs is limited by seven, and every single slot can extend over one or more slots, as shown in the previous chapter in Figure 2.

The PAN coordinator responsible for GTS allocation and management is based on the available capacity of its superframe. It satisfies two conditions i.e., the remaining length of its CAP higher than a MinCAP Length (as represented in equation (2.4)) and the maximum number of GTSs that have not been reached. Also, according to standard definition, the PAN coordinator scheduling GTS by the first-come-first-serve (FCFS) algorithm. The GTS allocation process step is shown in Figure 5. At first, the associated device that wants to allocate a new GTS must send predefined command, called the GTS request command. The PAN coordinator sends an ACK frame, which indicates that the GTS request has been received successfully.

The frame format of the GTS request command is shown in Figure 6. It contains GTS characteristics according to the requirements of the requesting device such as GTS length, GTS direction, and features type, respectively. The GTS length indicates the number of superframe timeslots being requested for the GTS. In contrast, GTS direction shows the transmission flow, either transmit or receive, besides, the characteristics type defines the GTS command purpose either GTS allocation or deallocation.

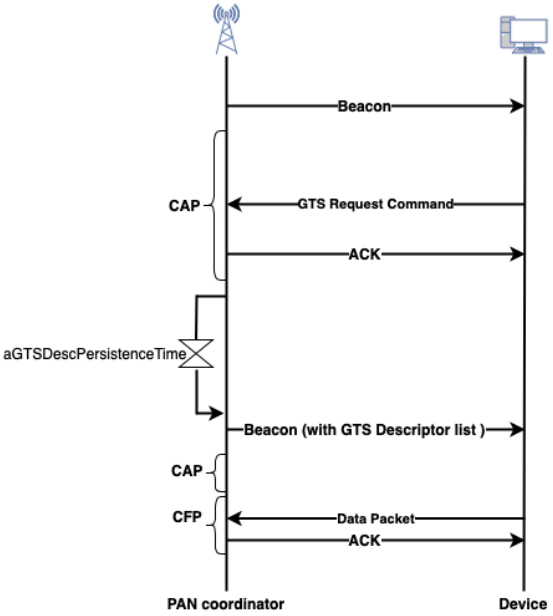

Figure 5: The GTS allocation sequence chart

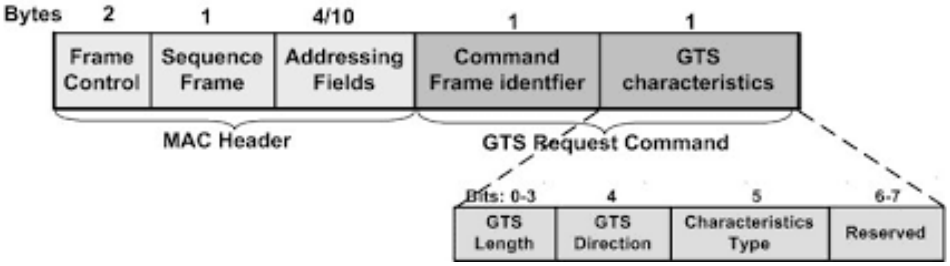

Figure 6: Frame format of a GTS allocation commend

On receipt of the GTS request command, the PAN coordinator either accepts or rejects the command on the bases of the superframe capacity. If the PAN coordinator has available capacity, it receives GTS request and updates the Final CAP slot by decreasing CAP length. Also, create a new entry in the GTS descriptor list; for each new GTS device, it stores the device short Address, set the GTS starting slot field value to the superframe slot at which the GTS begins, and set the GTS length field value to the length of GTS of the superframe. By contrast, if the PAN coordinator does not have available capacity in the current superframe, it sets the Start Slot value in the new GTS descriptor to 0 and the GTS Length value to the most substantial GTS length that can currently be provided.

Then, the PAN includes the GTS descriptor in the following beacon to announce the allocation information. On receipt of the beacon, the GTSdescriptor uses its dedicated bandwidth to transmit the packet within the CFP to the PAN coordinator by the ALOHA mechanism. By contrast, if the PAN coordinator does not have enough capacity, the GTS allocation request is rejected, and the device sends its packet in CAP.

According to the IEEE802.15.4 standard, the length of a single GTS time slot is the same as a single CAP slot, which means 1 CAP slot= 1GTS slot = SD/16, as mentioned in equation (2.3). The time of packet transmission during GTS is less than GTS duration; thus, GTS slot bandwidth is not filled. This leads to waste a significant amount of bandwidth for every slot allocated in every superframe, as shown in Figure 7. This problem is called the bandwidth underutilization problem and represents a shortcoming in protocol standard. The second shortcoming, the maximum number of GTS requesting devices is limited to seven devices, which leads to a lack of scalability.

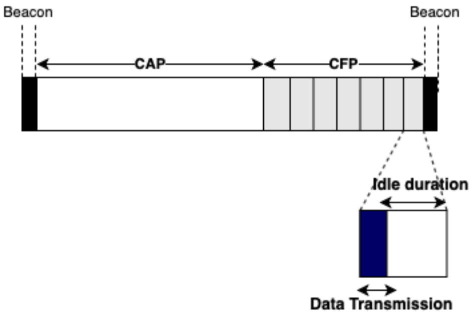

Figure 7: Duration of data transmission in single GTS slot

3.2. Bandwidth-Oriented Allocation of GTS Slots for IEEE802.15.4

As mentioned in chapter 1, our proposed scheme targets the beacon-enabled mode based on a star network. It designed to eliminate the slot size-induced bandwidth waste problem and increase scalability. Our proposed scheme is applicable over a wide range of LR-WPAN applications, especially applications requiring dedicated data bandwidth or time-critical, which means appropriate for lightly loaded networks. For example, remote-sensing applications.

In contrast to the original standard of protocol, in our GTS allocation scheme, the PAN coordinator divides the CFP section into varying lengths of GTS based on the desired data length of GTS requesting devices. It also allows for the allocation of GTSs of more than seven devices in the same superframe, as long as the superframe availability capacity condition is satisfied. In our GTS allocation scheme, the superframe shall have available ability to satisfy only one condition. That is if the length of the CAP is higher than *aMinCAPLength* (calculated by equation (2.4)).

To measure the single GTS duration accurately, we need to determine the total transmission time for each device requesting GTS. Note that the PAN coordinator shall ensure that each slot of GTS in CFP can accommodate a successful frame transmission cycle. In other words, the process of data transmission, the reception of the corresponding ACK frame, and interframe spacing (IFS) period must be completed before the end of the slot. For more knowledge, The MAC layer used the IFS duration to separate two successive frames to provide enough time to process received data. As shown in Figure 8, If the data frame length is greater than the maximum frame size (*aMaxSIFSFrameSize* = 18 byte) shall be followed by a long interframe spacing (*LIFS* = 40 symbols) period. Otherwise, the data frame shall be followed by a short interframe space (*SIFS*= 12 symbol) period.

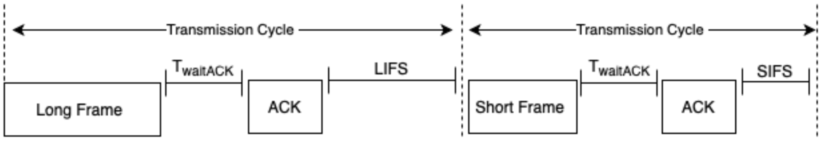

Figure 8: Transmission cycle (DATA-ACK-IFS)

Let us denote T_f to be the final total time, which refers to the amount of time required to transmit one data frame and receive an ACK frame, which can be calculated by Equation (3.1).

$$T_f = T_{data} + macAckWaitDuration + T_{LIFS} \tag{3.1}$$

Where T_{data} can be calculated by dividing the size of the required packet (can be obtained from the GTS length field) by the data rate (equals to 250000 bps due to operating in 2450 MHz band). T_{LIFS} can only have two values, either 48 bit or 160 bits depending on the length of the transmitted packet, as mentioned early. Finally, the *macACKWaitDuration* refers to the maximum waiting time for the acknowledgment frame to arrive. According to the IEEE 802.15.4 standard [3], *macACKWaitDuration* is defined as

$$\begin{aligned} macAckWaitDuration = {} & aUnitBackoffPeriod + \\ & aTurnaroundTime + phySHRDuration. \\ & + ceiling(6 \times phySymbolsPerOctet) \end{aligned} \tag{3.2}$$

Where, in this thesis, we have considered the O-QPSK PHY modulation scheme. As a consequence, *aUnitBackoffPeriod, aTurnaroundTime, phySHRDuration,* and *phySymbolsPerOctet* have fixed-predefined default value equal to 20, 12, 10, and 2, respectively. Besides, the number 6 in the equation refers to the sum of octets of the PHY header and the PHY Service Data Unit (PSDU) in the ACK. After calculating T_f, the PAN coordinator calculates an exact start time for the GTS slot (*GTSStartTime*), which can be calculated by Equation (3.3).

$$GTSStartTime = finalCAP - T_f \tag{3.3}$$

Where the *finalCAP* refers to the end of CAP duration before receiving the new GTS request. In general, at the beginning of the superframe and before allocating any GTS, the *finalCAP* is initialized to the same value of SD (end of active period) and compute the *aMinCAPLength* by equation (2.4).

Finally, the PAN coordinator allocates new GTS if the value of *finalCAP* is higher than the pre-calculated *aMinCAPLength* value. This means the minimal size of the CAP is not reached. Otherwise, the GTS request is rejected.

For more details about our scheme discussed in this chapter, the algorithm below shows the execution of our GTS allocation scheme with two phases: the initialization phase and the GTS allocation phase. The algorithm follows the flowchart in Figure 9.

```
Algorithm 1: GTS allocation scheme
Inputs: BO, SO
1. Initialization
     • Calculate the beacon interval (BI), according to (1)
     • Calculate the superframe duration (SD), according to (2)
     • Calculate the minimum CAP duration, aMinCAPLength, according to (4)
     • $totalGTSDuration = 0$
     • $finalCAP = SD – totalGTSDuration$
2. If (GTS request command received)
// The request includes the size of transmitted data, $T_{data}$
     - Send Ack to sent device
3.   If (requesting device is associated && not allocated GTS slots)
4.      $T_f = T_{data} + macAckWaitDuration + T_{LIFS}$
5.      $GTSStartTime = finalCAP – T_f$
6.      If ($GTSStartTime < aMinCAPLength$)
7.         GTS request rejected
8.      Else
9.         $finalCAP = GTSStartTime$
10.        $totalGTSDuration = totalGTSDuration + T_f$
11.     Add the device address, GTSStartTime, and $T_f$ to the GTS descriptor
```

```
        End if
    End if
End if
```

1. **Initialization Phase:**

This phase occurs at the beginning of the superframe and consists of four steps:

1.1. According to SO and BO values, represented as input by the user, the PAN coordinator calculates initial values for *BI, SD*, and a*MinCAPLength* according to the equations above 2.1, 2.2, and 2.4, respectively.

1.2. The total allocated GTS duration (represent the CFP duration) is initialized to zero.

1.3. The exact value of *finalCAP* is calculated by subtracting the total allocated GTS duration from SD value (Active period duration).

1.4. Finally, the PAN coordinator must include these values such as *BI, SD,* and *finalCAP* in its beacon and broadcast it in the network.

2. **GTS Allocation Phase:**

This phase occurs in the CAP duration and if the GTS command is successfully received. The PAN coordinator performs the following steps to allocate a new GTS:

- Send the ACK frame to inform the device of the safe receipt of the GTS request frame.
- It first checks if the sent device unknown, not associated, or previously allocate GTS slot; then the forwarded request will be rejected. Otherwise, the PAN coordinator check if there is available capacity in the current superframe to allocate new GTS as follows:
    - Upon to data length stored in the sent GTS request, the PAN coordinator calculates the total required time (T_f) to determine the exact extent of the GTS, according to equation (3.1).
    - Calculates the actual start time of the GTS slot (*GTSStartTime*) to ensure the satisfaction of the "available capacity" condition, according to equation (3.3).
    - Checks if the calculated GTS Start time is less than *aMinCAPLength* (the status of available capacity is not satisfied). It rejects the sent GTS request by creating a device GTS descriptor and sets the Start Slot of the device in the descriptor to 0 and the GTS Length to the most substantial GTS length that can currently be supported. Otherwise, the condition is satisfied, and the GTS request is accepted. Accordingly,

the PAN coordinator will update the value of *finalCAP* to be equal to *GTSStartTime*. Also, the total allocated GTS duration (*totalGTSDuration*) will be increased by adding the final total required time (T_f).

- Finally, it creates a new entry for the GTS requesting device in the GTS descriptor list, as the same way in the standard (as described in the section mentioned above).

3. **Our scheme repeats step 2 until the end of the superframe.**

In other hand, On the receipt of the beacon with the GTS descriptor, the device follows the same way in the standard to utilize its GTS slot. If it finds its corresponding short address, otherwise, it will send its packet in CAP by using CSMA/CA.

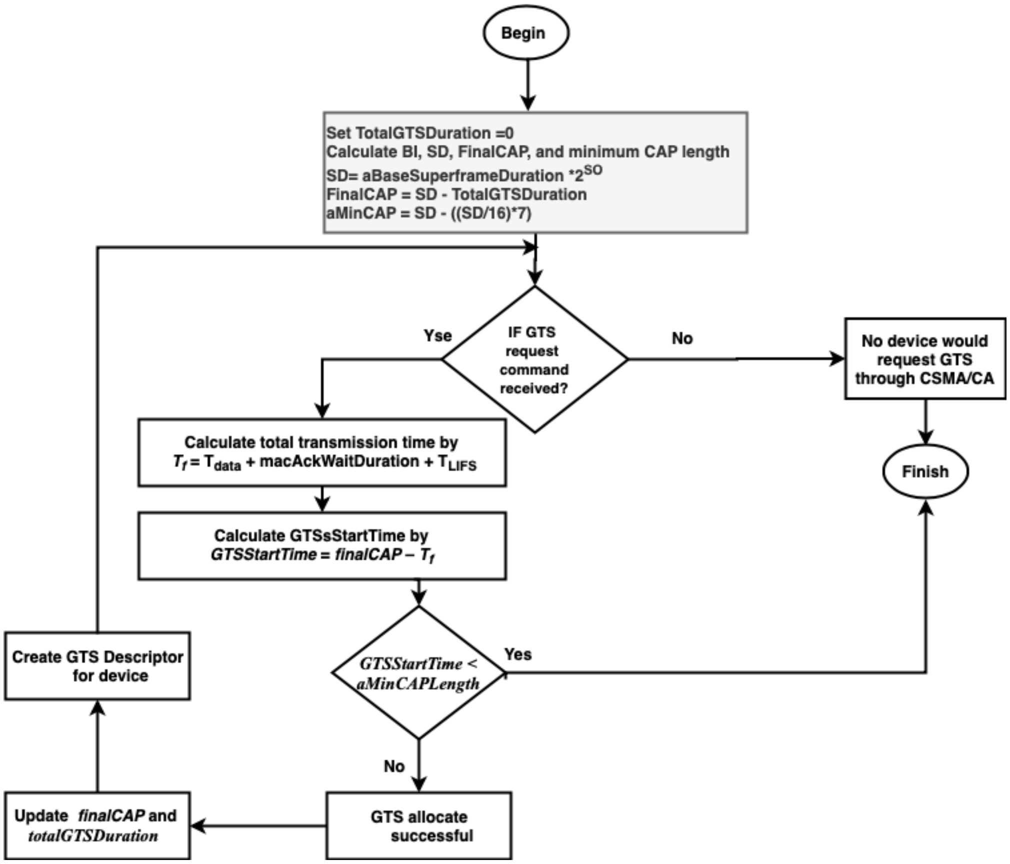

Figure 9: Flowchart of our GTS allocation scheme

Figure 10 shows a comparison between our GTS allocation scheme and the GTS allocation in the protocol standard. In brief, the utilize of the GTS with variable-length in the CFP led to an increase in the number of GTS slots in CFP, thus allow to allocate these slots to the maximum number devices in the network. As a result, our scheme overcomes of lack of scalability of the original standard.

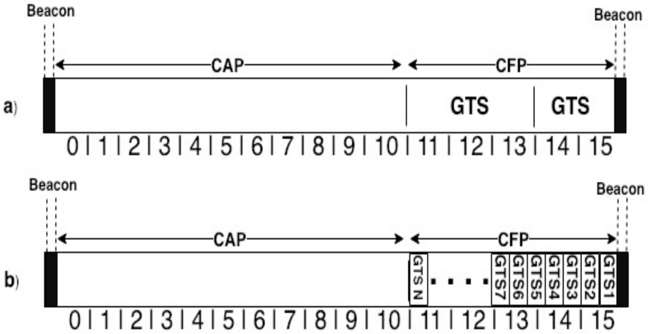

Figure 10: Comparison between the GTS allocation of our proposed scheme and that of the original standard.

Note that during implement GTS allocate process, some slot in CFP may still unused (unallocated). The reasons behind that, the remaining slots have either not been requested yet or not enough for the requesting device requirements. In this case, the remaining slots are embedded to CAP.

Chapter 4

An enhancement on IEEE802.15.4 Protocol’s sleeping schedule with B-MAC integration

4. An enhancement on IEEE802.15.4 Protocol’s sleeping schedule with B-MAC integration

In this chapter, we discuss the second part of our thesis schemes called An enhancements on IEEE802.15.4 Protocol's sleeping schedule with B-MAC integration. This chapter is divided into three sections. The first section provides an analysis of the duty cycle of the original standard and its shortcomings. Section 2 provides a quick overview of how the B-MAC duty cycle works and what is the similarities and differences between B-MAC and the IEEE 802.15.4. Finally, section 3 describes our proposed scheme in detailed.

4.1. Standard duty cycle Analysis:

Since the MAC layer duty cycle scheduling is probably the most effective way to save power, IEEE 802.15.4 MAC provide inactive periods in which the coordinator and associated devices turn OFF their transceivers for a specific time. This duty cycle controlled by setting two superframe parameters, *macBeaconOrder* (BO) and *macSuperframeOrder* (SO), as follows: $BO > SO$ (the inactive period present). In detail, at the beginning of each superframe, the PAN coordinator calculates the *BI* and *SD*, as represented in Equations 2.1 and 2.2, respectively. Then, The PAN coordinator must include these parameters in its beacon and broadcast it in the network.

On receipt of the beacon frame, each device set up its own sleep/wakeup schedule (timer) corresponding to the *BI* and *SD* values broadcasted in the beacon. In fact, the PAN coordinator and its associated devices schedule their start sleep timer (turn OFF their transceivers) at the end of the active portion (equal to SD value). Also, they schedule their wakeup timer (turn ON their transceivers) at the end of the superframe (equal to BI value) to receive next beacon. According to the protocol standard, the time in the sleep mode of the node equal to the duration of the inactive period, which can be conveniently calculated as follows.

$$T_s = BI - SD \tag{4.1}$$

Actually, IEEE 802.15.4 protocol has been intensively used for in a wide range of applications focused on a specific requirement such as prolongation of network lifetime for monitoring applications, in addition to other requirements in terms of delay and throughput of industrial applications. To satisfy these QoS requirements, it necessary to select the appropriate duty cycle based on the optimal operating mode for their required traffic load, be it dense, medium, or light. The duty cycle can be defined as the ratio of the duration of the active period (SD) to the duration of the whole superframe (BI).

$$DC = \frac{SD}{BI} \tag{4.2}$$

Therefore, the incorrectly determine the duty cycle may cause increased energy consumption or transmission latency. In other words, if set duty cycles as low (high sleep time), it may cause the worst-case transmission latency. The reason behind that is during sleep mode; the packets stay in the output queue until to the next superframe to become ready to transmission. Otherwise, when set duty cycles as high (short sleep time), it may consume more energy because the nodes shall be awake most of the time.

One of the limitations related to the sleep schedule of the standard was pointed out in [42] is the original standard does not define the optimal selection of the duty cycle corresponding to application requirements. Another limitation is the PAN coordinator sets a fixed duty cycle for all its associated nodes without considering the state of the node's battery into the scheduling process, which means all nodes wake up and sleep at the same time. Therefore, this fixed duty cycle performs poorly under very low of traffic congestion or duty cycle (under 1%) especially in applications requiring low latency networks (with a small delay). Figure 11 shows the duration of sleep time (sleep delay) of nodes over different BO values under the fixed-duty cycle of the standard, as represented by 1 (In this example, we fixed SO to 7). As seen in figure 10, the transmission delays caused by sleep time may be extremely high, e.g. T_s= 259 sec at SO=7 and BO=14.

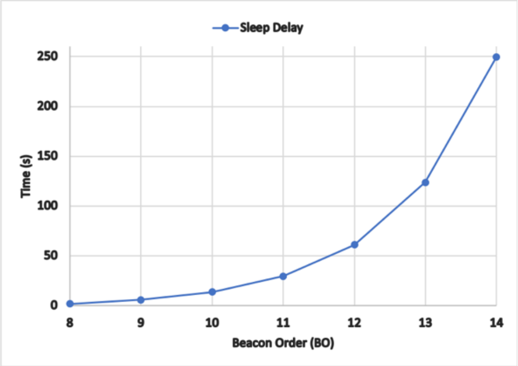

Figure 11: Duration of sleep time (SO=7)

Table 3 also gives the values of the time sleep and duty cycle based on the assumption of our example (SO=7, SD= 1.96608) for different BO values.

Table 3: The sleep time and percentage of duty cycle

BO	BI	Sleep Delay	Duty Cycle
8	3.93216	1.96608	50%
9	7.86432	5.89824	25%
10	15.72864	13.76256	13%
11	31.45728	29.4912	6%
12	62.91456	60.94848	3%
13	125.82912	123.86304	2%
14	251.65824	249.69216	1%

4.2. Overview of B-MAC duty Cycle

As mentioned in chapter 2 (section 2.1), B-MAC is one of the considered protocols (the famous technical Low Power Listening) use an adaptive preamble sampling scheme.

In this scheme, the nodes stay in the sleep state most of their time (turn OFF its transceivers) and only awake in pre-determined time to sensing the channel if the packets are destined for them. Transmission state describes as follows: each node has a data frame to send, it shall sense the medium first by using Clear Channel Assessment (CCA) if idle, waits little time called back-off and then send a preamble followed by data frame and go back to sleep after receiving ACK if present. If the receiver node detects a preamble, it stays awake until receiving the whole preamble and checks if it is the node that the frame is destined for. If it is, it extends its active duration (wakeup interval) to receive the packet; otherwise, it turns off its transceivers and enters to the sleep mode. Note, the duration of the preamble should be longer than the active duration (wake up interval) to guarantee it can be caught by receiver nodes. Figure 11 shows the B-MAC duty cycle operation.

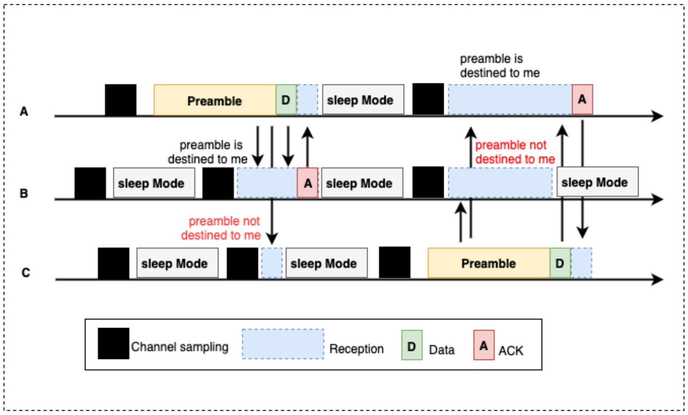

Figure 12: B-MAC duty cycle operation with LPL

4.2.1. The similarities and differences between B-MAC and the IEEE 802.15.4:

Generally, most of the WSNs protocols target MAC layer to apply their approaches based on applications requirements. Therefore, we make a comparison of the MAC functionalities offered by both B-MAC and IEEE 802.15.4.

There are several similarities between these protocols:

1. Beacon frame and the Preamble in B-MAC can be used to achieve the same goal.
2. In the IEEE 802.15.4 beacon-enabled mode, the PAN coordinator periodically broadcast beacons to synchronize nodes at the beginning of each superframe. And in B-MAC, a node periodically sense the shared channel. If it detects the preamble, it stays awake to receive a packet.
3. In the IEEE 802.15.4, nodes access the channel by using the CSMA/CA mechanism, in both modes beacon-enabled and non-beacon-enabled. And in B-MAC, nodes use the clear channel assessment (CCA) to access the channel, which considers as a kind of CSMA/CD mechanism.
4. Both IEEE 802.15.4 and B-MAC are using ACK frame in order to achieve high transmission reliability.

Although several similarities exist between the 802.15.4 and B-MAC, differences also exist between them:

1. In the IEEE 802.15.4, the beacon frame is an optional choice. During non-enabled beacon, all nodes in the network using unslotted CSMA-CA to access the channel. Whereas, In the B-MAC, the preamble is a forced choice.

2. Beacon frame has very short length compared to the preamble frame length; preamble shall be longer than sleep time of the node in order to increase the probability of preamble detection.
3. IEEE 802.15.4 provides GTS for applications requiring dedicated bandwidth while the reservation mechanism is not supported in the B-MAC.

4.3. Our proposed sleeping schedule scheme

For applications require low latency under a specific duty cycle, most of the MAC protocols makes a trade-off between energy-efficient and latency in order to offer optimal performance. For this purpose, we propose a dynamic scheduling scheme targeted to achieve high performance in terms of low power consumption and latency minimization. It is suitable for environmental monitoring and low-latency event-driven applications.

In addition, our sleep schedule technique enables high-duty-cycle operation (100%) by sets the SO = BO values (there is no Inactive Period) without sacrificing the power consumption efficiency. Generally, the idea of our sleeping schedule based on the method of a sleep/wakeup scheme of the B-MAC with additional modifications. The “long preamble “is ignored in this scheme due to three reasons: 1) the functional similarity between the beacon and the preamble, in addition to, beacon length feature, as mentioned in the previous section. 2) In the B-MAC, the preamble enables the communication between nodes, means the device uses it to wake up neighbors’ devices. Whereas, we consider star topology, where all communication is done through the PAN coordinator (no communication among nodes). 3) Due to the downlink frame transmission mechanism in the IEEE802.15.4 standard. Figure 13 shows the downlinks transmission procedural. In detail, When the PAN coordinator wants to transfer data to a particular device, it shall first add a device address to the pending address field in the beacon frame. After receiving a beacon, each device checks if its address has been announced in the pending list or not. If it is, the device sends the poll command to request its data. On receipt of the poll request, the PAN coordinator send ACK followed by device packet if present.

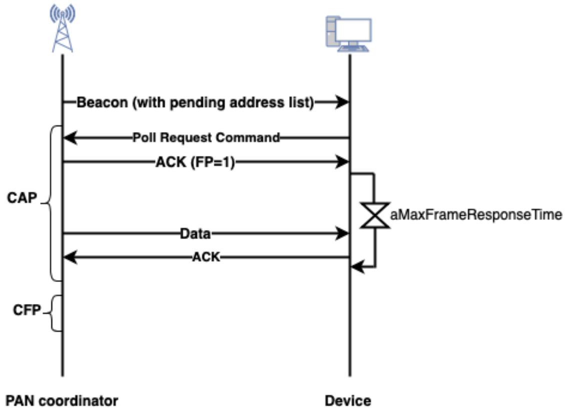

Figure 13: The downlinks transmission procedural

During our sleep scheduling, a node shall awake up only in three cases: at the beginning of each superframe to receive the beacon, if it has data to send, and to utilize its GTS pre-allocated. The reason behind that to we intent reduce the energy consumption caused by waiting for events to happen. Note that is when a node enters sleep mode, it only turns OFF its transceivers (Radio is OFF) while its processor still running and able to detect network event [43].

Algorithm 2 shows the cases of waka up in our sleeping schedule that follows the model of the finite state machine (FSM) of devices in Figure 14.

First case: in the beginning and after receiving the first beacon, each device stores the superframe information of chosen PAN coordinator. For example, the beacon order (BO), superframe order (SO) and final CAP. Also, the device schedules a new wakeup message to receive next beacon according to BO value in the beacon received. Then, it checks if that beacon comprises a GTS descriptor corresponding to its address or not. If it is, it schedules a new wakeup message according to its GTS descriptor.

Algorithm 2: Sleep/wake-up scheme

```
1.  If (Beacon received)
    -   Schedule new wakeup timer for next beacon.
    -   If (the device address present in GTS allocation List)
            o   Schedule new wakeup timer in CFP.
    -   If (the device address present in pending message List)
            o   Send request command to poll pending by CSMA/CA
                    ▪   If (ACK has arrived PF ==1)
                            •   Still awake until aMaxFrameResponseTime.
                                    o   If (Pending msg received && use ACK)
                                            ▪   Send ACK
                                        ELSE
                                            ▪   Turn OFF transceivers.
                                        End if
                        End if
        End if
        End if
    -   Turn OFF transceivers
End if
2.  If (has packet to send)
    -   Turn ON its transceivers & transmit packet
            o   If (ACK has not arrived && retry limit not reached)
                    ▪   Retransmission packet
        ElSE
                    ▪   Turn OFF transceivers.
        End if
    End if
3.  If (a wake-up self-message received)
    -   If (GTS allocated time)
            o   Turns ON its transceivers for a determined time.
            o   Turn OFF transceivers.
    -   ELSE
            o   Turns ON its transceivers to receive beacon frame.
        End if
End if
```

Also, it checks if that beacon has been announcing pending messages corresponding to its address or not. If it is, it sends a poll command to the PAN coordinator by using CSMA/CA and waits for the acknowledgement. As shown in FSM, the device stays awake for a specified time (*aMaxFrameResponseTime*) if the received ACK indicates that it has a pending frame (FB=1). If it received its pending message within the specified time limit, the device replies with an ACK frame and enter to sleep mode (turn OFF its transceivers). Otherwise, the device enters sleep mode if the specified time (*aMaxFrameResponseTime*) is expired, or if the received ACK from The PAN coordinator indicates not to have pending frames (FB=0).

The second case: if a device has a packet to send, it enters to active mode (turns ON its transceivers) to send its packet to the PAN. FSM shows clearly that the MAC layer of the sender device receives a notification from its upper layer indicating to the event happened. Then, the device sends its packet by CSMA/CA and wait for an ACK reply from the PAN coordinator. The device stays awake and retransmission its packet if the ACK packet don not received within specified time and the available number of retransmissions has not yet been reached. Differently, if received ACK successfully or does not have the attempts of retransmission, it enters to sleep mode.

Finally, the third wake up case occurring when a wakeup self message is received. If that self message indicates to GTS allocated time, the device turns ON its transceivers until its determined time expired and then goes back to sleep. Otherwise, it indicates the time of the next beacon. Therefore, the device awakes up until beacon received and repeat the process mentioned in the first case. It is important to point out that in our scheme, unlike to protocol standard, all devices determine their own sleep/wake up schedules based on their state. That is the reason why we call our sleep schedule a dynamic sleep schedule.

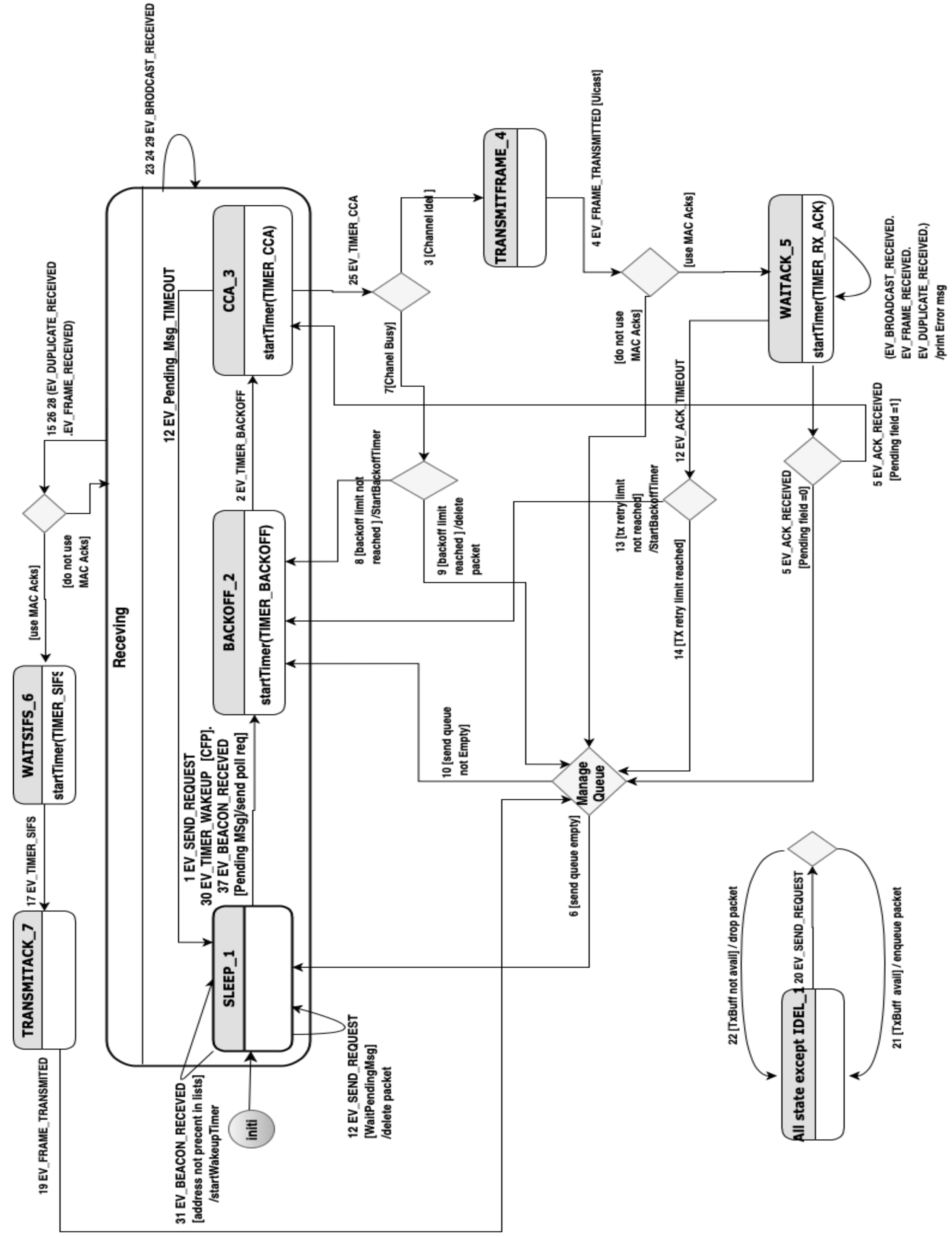

Figure 14: Finite state machine of devices

Chapter 5

Experiment and Results

5. Experiment and Results

In this chapter, we introduce the performance results obtained by using OMNeT++/INET-Framework to simulate the two proposed enhancement on IEEE802.15.4 Protocol's — Bandwidth-Oriented Allocation of GTS Slots and sleeping schedule with B-MAC integration— discussed in Chapter 3 and 4, respectively. The brief overview of the network simulator and the shared assumptions of the considered schemes in terms of deployed network topology, IEEE802.15.4 MAC operation mode, and the configuration and parameters settings of the IEEE 802.15.4 chosen PHY layer is shown in the first section of this chapter. Following this illustrative section, the next two sections analyze the simulation results of the two proposed enhancement schemes in terms of different performance metrics based on proposed schemes objectives. Each of these sections describes their simulation scenario and discusses its different results in detail compared to the IEEE 802.15.4 standard.

5.1. Simulation environment

To evaluate the performance of proposed enhancement schemes, we considered Object-oriented Modular Network Simulator (OMNET)++ operating platform [44]. OMNet++ is open source and support a significant network simulation framework such as Castalia [45], MixiM [46], and INET [47]. In this thesis, all experiments are simulated by using IEEE802.15.4 models, which are already included in INET frameworks and implemented in the OMNeT++ simulator.

Figure 15 shows the composition of the IEEE 802.15.4 module wireless node. It composed of basic modules: application layer to generate packets, network layer to implement MAC services primitive and forwarding packets, network interface card (NIC) which compose of the MAC layer and the radio, and energy modules. In this thesis, we performed two different sets of experiments to evaluate the performance of each of our proposed enhancements schemes.

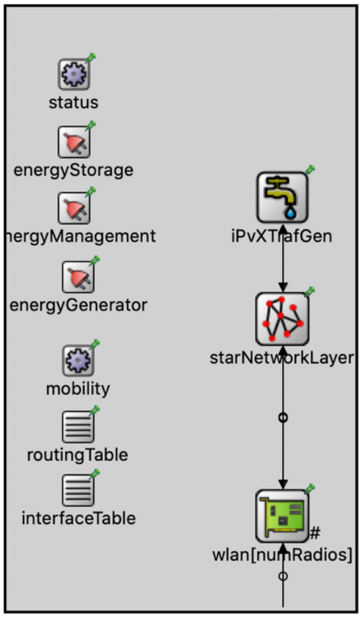

Figure 15: IEEE802.15.4 device Module

We focus on a beacon-enabled star PAN network because we need to test our schemes without any influence from the higher layers. It is consisting of many RFD devices connected to a central PAN coordinator and deployed randomly in a network. In addition, our network operates in the 2.4-GHz PHY frequency band with 16 channels (ISM band) to get higher transmission bandwidth with raw data rate 250kbps. We remove the inactive period by setting BO=SO in order to achieve a low transmission latency (lower a sleep delay). Moreover, we assume that the ACK confirmation is present to achieve more reliability. In our energy consumption simulation, we used the *StateBasedEpEnergyConsumer* as the energy consumer module. The remain simulation parameters used to model the WPAN and their default values are summarized in Table 4.

Table 4 Used simulation parameters

Parameter	Value
queueLength	10 packet
Bitrate	250 Kbps
ccaDetectionTime	0.000128 sec
useMACAcks	True
BO=S0	2,3,4,5,6
BEmin	3
BEMAX	5
PWRtx	100mw
PWRrx	10mw
PWRidle	3mw
PWRbusy	5mw

5.2. Bandwidth-Oriented Allocation of GTS Slots – simulation result

The effectiveness of our GTS allocation scheme has been rigorously evaluated against that of the IEEE802.15.4 standard and the existing techniques in previous studies, as aforementioned in Chapter2. These previous allocation works have used the same division technique for CFP, which is the fixed-length timeslots; therefore, their performance results are close to each other. For this, we suffice by considering the slot splitting technique, proposed in [31], in our evaluation process. To test the performance of the new scheme, we ran experiments for different SO/BO values (2,3,4,5 and 6) to thoroughly study the performance impact measures in term of the maximum number of devices can reserve GTSs, network throughput and the residual energy capacity.

Figure 16 shows the number of devices that are successfully allocated using our scheme as well as those of the original standard and the slot splitting technique. Overall, our scheme accommodates a different number of devices exceed that which can be accommodated by using the standard and slot splitting techniques for all different values of SO. You can clearly see that, for SO greater than or equal 4, there has been a sharp increase in the number of allocated devices by using our scheme, while the number of allocated devices in the slot splitting technique and original standard remained constant by 14 and 7, respectively.

Although the slot length in CFP is increasing as the SO value increases, the original protocol and the slot splitting technique could not obtain the maximum benefit from that; where the maximum possible devices are limited by 7 and 16, respectively. In contrary, our scheme significantly outperforms them in the GTS allocation for a large number of devices in the same superframe. For instance, for SO=6, the number of allocated devices close to 70, which represents the total number of devices used in our experiment. The result proves that our scheme exploits the increase of CFP by allocating a maximum number of devices at the same superframe in order to eliminate the waste of bandwidth. In addition, our scheme applicable in bigger networks with a large number of devices.

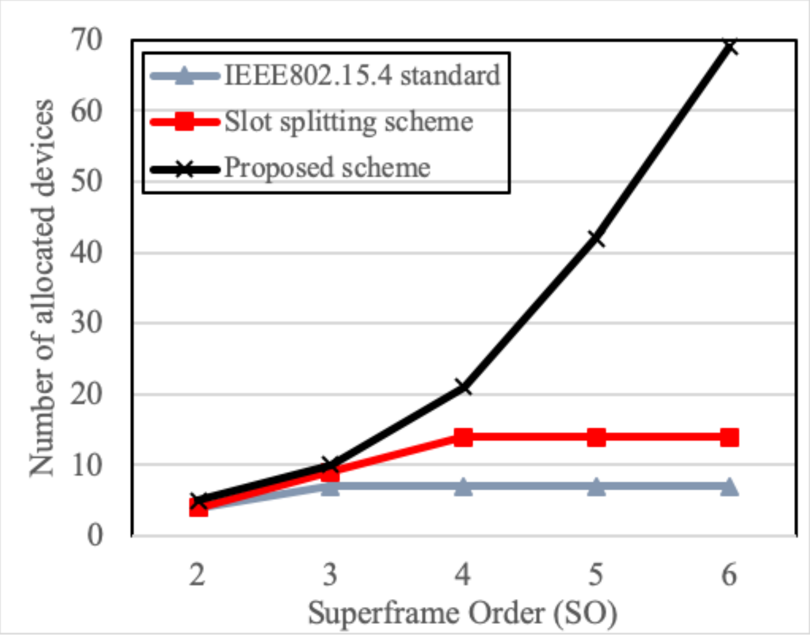

Figure 16 Comparison between the numbers of allocated devices in the same superframe

Figure 17 presents the average throughput of our scheme and the two considered techniques for various SO values. The throughput can be defined as average successful transmits received by PAN coordinator per unit time, that plotted in the y-axis. Overall, despite differing pattering between the GTS allocation schemes, the avrege of throughput incresesd gradually for different SO values.

As the figure shows, our scheme achieves higher throughput than that of the two techniques. For SO =6, the percentage improvement in throughput gained from using our scheme rather than that considered schemes are 28.4% to 5.9%, respectively. Throughput is increased because our enhancement scheme optimally exploits the bandwidth of GTSs by using variable-length timeslots; prevents any portion of the CFP from being left unused. As a result, our simulation results reveal that maximizing the throughput of the network under various SO settings and minimizing the slot size-induced bandwidth waste problem.

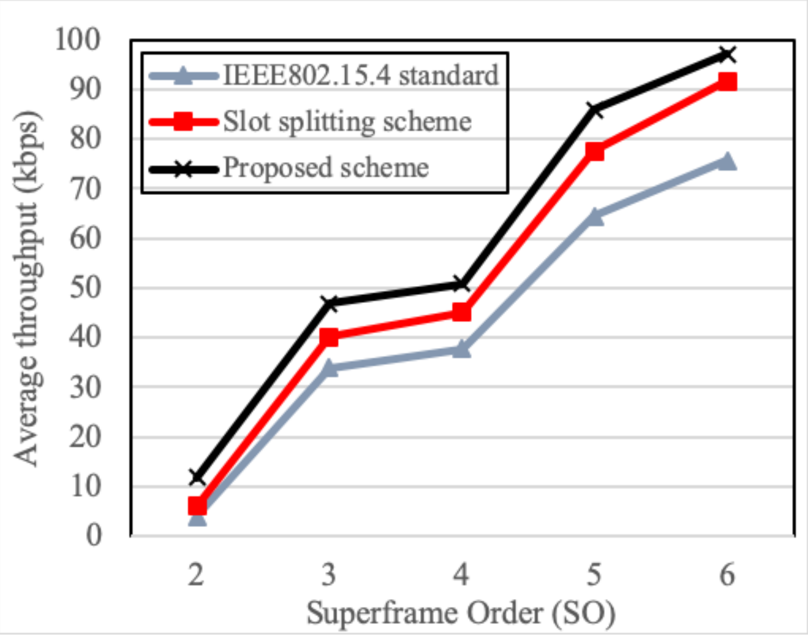

Figure 17: Comparison between the throughputs resulted from our proposed scheme, the original standard, and the slot splitting technique.

To study the effect of the extra required processing to GTS allocation in our scheme, we evaluate the amount of energy consumption for our enhancement scheme compared to the two considered techniques, represented in Figure 18. This figure illustrates the comparison of the residual energy capacity of our scheme, the original standard, and the slot splitting technique. The comparison results of the figure show that, as expected, our scheme consume more energy than the other two techniques, in particular, by increasing SO value. Another justification behind that increase of energy is the impact of the high number of packets received (maximization throughput efficiency), as represented in figure 16. Nevertheless, the result of our energy consumption is close or little more than the considered techniques. For instance, for SO=6, our scheme consumes only 0.0016 mJ compared to the original standard and 0.0012 mJ compared to the slot splitting technique.

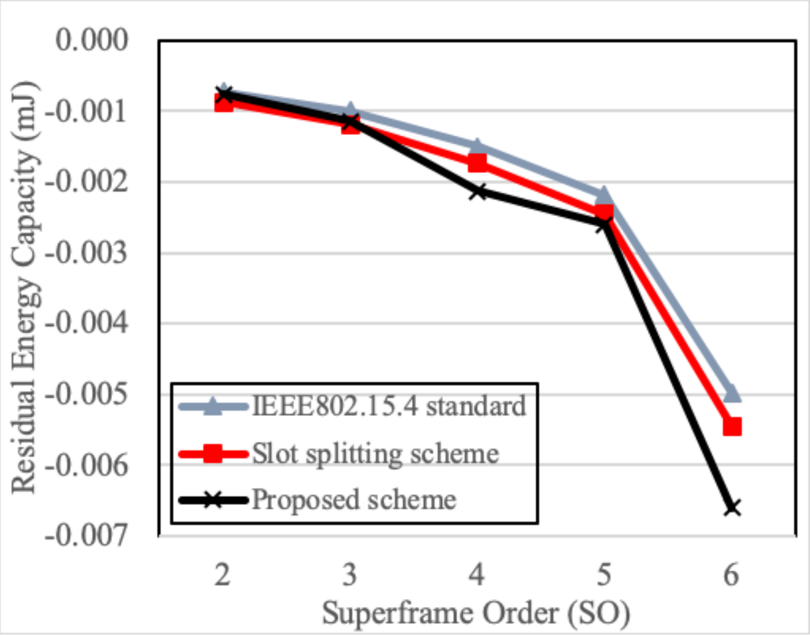

Figure 18: The residual energy capacity of our proposed scheme, the original standard, and the slot splitting technique

Our simulation results reveal that our GTS allocation scheme achieves at a satisfactory level in dense networks. Especially in terms of throughput, network scalability and the energy conservation; that insignificant extra energy consumption must not prevent utilization of our scheme on a wide range of applications in the monitoring field.

5.3. Enhancement sleeping schedule with B-MAC integration – simulation result

In this section, we performed several simulations experiments to evaluate the effectiveness of our sleep schedule scheme also under different SO values. Unlike the previous studies which require particular consideration (BO >SO), as mentioned in 2.2, our sleep schedule scheme designed for applications requiring a very high duty cycle (BO=SO), therefore, we suffice by comparing the results of our scheme with the original standard. The simulation scenario consists of one PAN coordinator and 20 RFD devices.

Once again, energy efficiency was the primary performance measure of interest in our sleep schedule scheme. For this purpose, Figure 19 shows the comparison of the total energy consumption of all the nodes in the network over different lengths of the active portion. overall, our scheme conserves more energy than of the original standard, especially for larger values of SO. For example, for SO =4, our enhancement sleep schedule consumed 30% less energy in comparison to the original standard. This increased level of energy conservation results leads to increase the network lifetime.

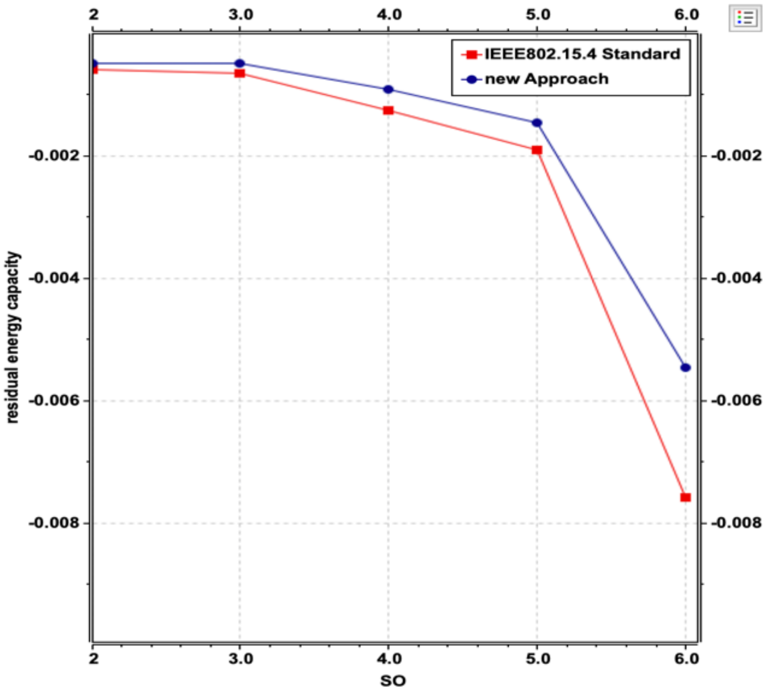

Figure 19: Comparison between the residual energy capacity resulted from our enhancement scheme and the original standard.

As we know WPAN networks work in a space the size of a room or a hall, therefore, high simultaneous transmission of packets among devices, high interference can occur. Which lead to spends unnecessary energy in each device during idle mode. To obtain our objective, we evaluate the interference computation of our scheme and compare it to the origin standard. Figure 20 shows the count of network interference of our proposed scheme and the original standard in which the y-axis represents the simulation time in milliseconds times. overall, interference of the network increases dramatically as the SO value increases.

We can clearly see that our proposed scheme minimizes the interference by about 18% when SO equals 2 and this percentage is increased to be 30% when SO equal 6. The Interference reduction leads to minimizing collision rate and therefore retransmissions are reduced, will result in a considerable saving in energy consumption.

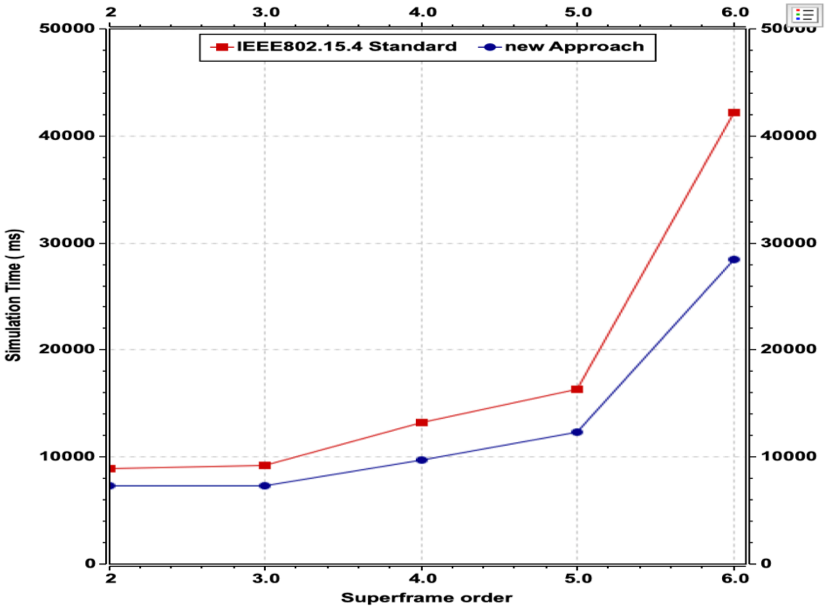

Figure 20: Comparison of Interference computation between our enhancement scheme and the original standard

Consequence, by extending the lifetime of the individual sensors the efficiency in the performance increases. Figure 21 shows the network throughput of our enhancement scheme and the original standard. It can be seen that for SO equals 2, our scheme achieves slightly lower throughput than the original standard because turn ON/OFF in this scheme may consume some time which effects on the bandwidth metric. Otherwise, as expected, as the SO value increases, the total throughput of our enhancement scheme increases too. For example, for SO equals 6, our scheme achieves an improvement in overall throughput by approximately 30%.

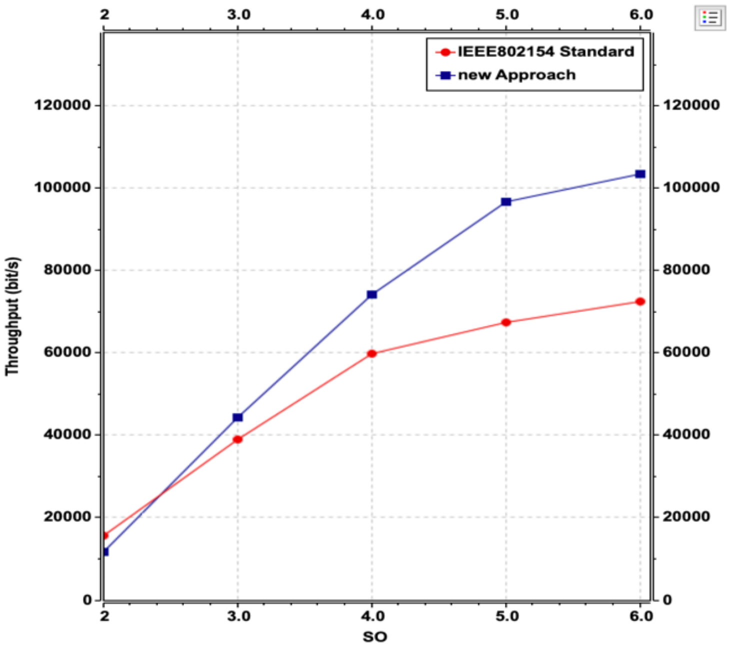

Figure 21: Performance comparison as regrades throughput between our scheme and the original standard

Chapter 6

Conclusion

6. Conclusion

In LR-WPAN, IEEE 802.15.4 protocol has grown important since its inception, and it needs to continue to improve to keep providing high reliability, especially in the monitoring field. In our thesis. We try to improve the IEEE802.15.4 beacon-enabled mode in term of scalability, GTS bandwidth optimal utilization, and energy-efficiency by proposes two schemes. The first scheme, an enhanced Bandwidth-Oriented GTS allocation scheme targeted to eliminates the GTS bandwidth waste problem in CFP and the lack of scalability. This scheme works well for the large remote sensing monitoring applications under different traffic load. The second scheme, an enhanced standard protocol's sleeping schedule, aims to conserve sensor energy without compromising the low latency. This scheme is suitable for event-driven applications required delay-sensitive data. To experimentally validate our schemes, we performed two sets of experiments to study our schemes using the OMNet++ network simulator. The simulation result proves that the performance of our GTS allocation scheme is better than the original standard and those previous works, in term of the maximum number of GTS allocated devices as well as network throughput. Also, the results of the second scheme prove that our enhanced sleep schedule outperforms than the original standard in term of energy consumption, Interference computation count, and network throughput.

Chapter 7

Future Work

7. Future work

We plan to merge our proposed schemes into one scheme and investigate the throughput as well as more energy savings. Then, we intend to improve our work by employing a more efficient queue scheduling technique rather than the approved queue scheduling of the original standard. This is because the original standard uses First Come First Serve (FCFS) which lacks flexibility and inefficiency. After that, we plan to extend our work to include peer-to-peer topology.

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