A MAC PROTOCOL FOR HARSH INDUSTRIAL IoT APPLICATIONS

By

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Abstract

Heavy industries such as mining, constructions and transportation manufacturing are currently facing many dilemmas due to the critical and harsh conditions that they collide with during their operations. Such environments faces many challenges in managing the wireless communication due to the heavy equipment, large machine and wide areas that might cause failures in such systems. Thus, there is a great need for solutions to overcome those critical issues. We introduce single channel-MoT (SC-MoT) Medium Access Control (MAC) protocol that runs on top of LoRa physical layer. The protocol adapts the multiple channel protocol MoT for industrial applications enabling ease of implementation and lower cost and delay. SC-MoT uses LoRa modulation to offer an extended range of communication with high sensitivity and low noise. Similar to MoT, SC-MoT uses the centralized scheduling technique to achieve collision-free transmissions with low delays and long power source lifetime. In addition, features such as broadcasting and rapid acknowledging are also implemented in SC-MoT. We evaluate SC-MoT against MoT with respect to waiting times, energy consumption and cost. We also show results from field experiments in a harsh Industrial environment.

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WSN	Wireless Sensor Networks
IoT	Internet of Things
IIoT	Industrial Internet of Things
IERC	European Research Cluster on the Internet of Things
Industry 4.0	Fourth wave of the industrial revolution
IIC	Industrial Internet Consortium
AIOTI	Alliance for the Internet of Things Innovation
LoRa	Long Range
CSS	Chirp Spread Spectrum
MAC	Medium Access Control
MoT	Mac on Time
SC-MoT	Single Channel-Mac on Time
TRL	Telecommunications Research Lab
LPWAN	Low Power Wide Area Network
IoTSP	Internet of Things Services and People
SAN	Sensor Area Network
FSK	Frequency Shift Keying
SF	Spreading Factor
BW	Bandwidth
ALOHA	Additive Links On-line Hawaii Area
WAN	Wide Area Networks
PAN	Personal Area Networks

Chapter 1

Introduction

Currently, there is a significant spike in the use of wireless sensor networks (WSNs) in different domains. Many devices are now connected to the Internet gathering information and sensing the behavior of objects around us under the name of the Internet of Things (IoT). The collected data can then be used in many domains such as; smart cities, medical devices, pollution detection and transportation, to name a few. There is a wide range of IoT applications as their use can vary from simple entertainment applications to critical industrial and military purposes.

Recently, industrial facilities have been using IoT technologies under the term; Industrial Internet of Things (IIoT) [1]. IIoT is used for monitoring, safety and security to increase the productivity and improve the performance. Organizations such as the Internet of Things European Research Cluster (IERC) [2], the German platform known as the Fourth Wave of the Industrial Revolution (Industry 4.0) [3], Industrial Internet Consortium (IIC) [4]**,** Alliance for the Internet of Things Innovation (AIOTI) [5], focus on the potential opportunities IoT could have in the industry.

Connecting the things to the internet has never been an easy task. Industries such as construction, mining, production or medical services can be defined as critical applications. The critical applications are those who face harsh and urgent conditions due to the presence of metal objects, the wide range of area needing coverage, and the limited lifetime of the batteries. Therefore, the deployment of the IIoT in such environments faces additional challenges.

The communication in any network starts by the physical (PHY) layer. The PHY layer plays a significant role in the signal's range of communication. Therefore, one of the important aspects of employing an IIoT application is to choose the best PHY layer considering the needs regarding energy efficiency, the range, and the cost [6].

LoRa is one of the promising IIoT PHY layers [7]. LoRa uses the chirp spread spectrum (CSS) modulation capable of achieving long ranges that can reach up 10 kilometers with low transmission power and high sensitivity [8]. As most of the IIoT applications run on wireless networks, the medium access control (MAC) layer plays a role in achieving many of the IoT requirements unique to the industry. MAC protocols handle the channel traffic and control the access of the nodes to the channel. According to the channel access method, there are two types of MAC protocols running on top of LoRa PHY layer namely, contention-based and scheduling-based. The LoRa contention-based MAC protocols such as LoRaWAN have higher rates of collisions and higher levels of energy consumption caused by the retransmissions [9]. On the other hand, LoRa scheduling-based MAC protocols such as Symphony Link and MAC on Time (MoT) have demonstrated good performance due to the centralized synchronization between the nodes. MoT represents a guaranteed access collision-free MAC protocol, controlled by a centralized base station (BS). Compared to LoRaWAN, MoT shows significant improvement in waiting times, energy consumption, and maximum throughput. However, in many tracking applications in harsh fields, MoT may prove to be suboptimal, due to the delayed acknowledgment from the BS. In MoT the acknowledgment is sent after receiving multiple reporting packets.

MoT showed great potential to overcome many of the industrial dilemmas using LoRa PHY layer and the efficiency of the centralized scheduling. However, to meet the industrial critical applications, adjustment and more features should be added to MoT design. In this thesis, we introduce Single Channel-MoT (SC-MoT) a new MAC protocol designed on top of LoRa to overcome the drawbacks of MoT and make it suitable for harsh IIoT applications.

1.1 Motivation and Objectives

There is a massive expansion in the use of the Internet of Things (IoT), according to CISCO, there will be more than 50 billion devices connected to the Internet by 2020 [10]. The industry is considered one of the major areas in which the IoT devices are being deployed. Because of the needs of data collection and accurate tracking in many critical sectors, to help in achieving their industrial goals. Industries need IoT

deployment for monitoring and tracking tasks, creating machine to machine (M2M) communication and energy optimization. Environments such as; mining and military areas require efficient wireless systems that can assure low delays with minimum energy consumption, complexity, and cost. Furthermore, there have been many types of research focusing on improving the IIoT for commercial reasons for the benefit of manufacturing facilities. According to [11] by 2030 the expenses for developing IIoT will reach up to US$10.6 trillion per year.

The objective of our work is to create a new MAC protocol that can work efficiently above LoRa PHY layer within harsh IIoT environments. As aforementioned, MoT has a number of advantages making it suitable for many IoT applications. However, adaptations have to be made to make suitable for the harsh industrial applications, hence the introduction of SC-MoT. SC-MoT that has the following attributes:

1- **Low waiting time**: SC-MoT achieved lower waiting times by implementing deterministic scheduling.

2- **Acknowledging every packet**: SC-MoT acknowledges every packet making it suitable for many tracking applications.

3- **Downlink:** SC-MoT supports downlink, adding more properties to the system, for instance, sending command messages and supporting over the air programming.

4- **Low cost:** The protocol design uses simple hardware and a less expensive transceiver chip, offering a high reduction in the cost.

5- **Scalability:** SC-MoT supports scalability by supporting natural expansion with more BSs and nodes.

This work is a part of a long-term project within the Queen's Telecommunications Research Lab (TRL) and industrial partner Syncrude Canada Ltd. [12] to demonstrate the potential of deploying the IoT technology in the harsh oil field mining environment.

1.2 Thesis Contributions

In this dissertation our contribution can be illustrated in the following points:

1- We introduce SC-MoT, a new MAC protocol designed for the harsh IIoT applications. In addition, clarifying the adjustments and the additional features of our protocol compared to MoT. We evaluate the performance of SC-MoT against MoT in terms of waiting time, number of nodes supported, energy consumption and cost.

2- We implement the protocol on Velapulsar sensing platform [13]. The sensing nodes were prepared for a field deployment through protection procedures and range experiments.

3- We deploy the sensing nodes on the shovels used in the Alberta oil sands. We test and monitor the performance during the shovel digging operation.

1.3 Thesis Organization

Chapter 2 gives an overview of the harsh IIoT application and their requirements followed by a presentation of LoRa PHY layer and its MAC protocols. In chapter 3, we introduce our protocol, SC-MoT, illustrating the design goals and a breakdown of its model and calculations. The evaluation of SC-MoT is represented in chapter 4. Chapter 5 presents a deployment scenario for the protocol in a mine field. Finally, the thesis is wrapped up with conclusions in Chapter 6.

Chapter 2

Background

Different manufacturing companies have been facing significant challenges in achieving the targeted tasks due to the complexity of the systems, safety issues, financial reasons, and inefficient performance. In the last two decades, there has been an acceleration in the development of all IP-connected devices namely, IoT. Currently, the IoT is highly used in many different environments such as retail, medical, automotive, manufacture, and industry. Although the retail sector is still the highest domain in using IoT, the industrial IoT (IIoT) is showing a fast expansion in both the research and field implementations.

IIoT applications are more susceptible to harsh and critical situations. As they get deployed in severe environments, for instance, mining and construction sites. Thus, the high efficiency of the IoT systems in such environments is a priority.

The physical communication layer and MAC protocols play a significant role in the realization of IIoT. The physical layer modulates the wireless signal and manages its sensitivity to the noises. MAC protocols control the channel access and prevent collisions, and idle listening. Thus, studying the current MAC protocols is an essential task before any industrial deployment especially when the environment is harsh.

In this chapter, we define the IIoT and some of its applications. In section 2.1, we mention few of the harsh industrial environments and their main needs. Section 2.2 presents the role of the physical layer, highlighting a promising PHY layer namely, LoRa. Section 2.3 covers the classification of the MAC protocols applied on top of the LoRa PHY layer.

2.1 Industrial Internet of Things (IIoT)

The IoT is the interconnection between smart devices or nodes and the base station [14]. IoT aims to develop smart systems with a high level of connectivity between the things with reduced human interference. The IIoT not only assures human non-intervention but also introduces the autonomous feature to the machines [14]. IIoT promises to be a significant improvement in many directions, for example, tracking the manufacturing process, transportation, health, and security. Such improvements can be achieved by collecting and analyzing data from sensors with better efficiency and higher throughput in different operations.

IIoT applications are extended but not limited to, machine condition monitoring, machine to machine communications (M2M), energy management, data analytics and interconnected medical systems [14]. IIoT has been deployed in the industrial sector in recent years and has been showing promising opportunities to have a more efficient industrial environment. IoT services and people (IoTSP) [15] shows an overview of the existing and the expected performances of the factories and manufacturing companies by deploying the fourth wave of the industrial revolution (Industry 4.0) [3].

The range of IIoT applications can vary depending on the type of environment in which it will be deployed. We focus on the harsh environments and critical fields such as mining or construction industries. Such applications have higher risks and face dangerous situations that need more solutions.

2.1.1 Harsh Industrial Applications and Their Requirements

The range of requirements for industrial applications gets broader as it becomes more critical to cover their needs. In a factory, metal objects, very large spaces, extreme temperatures and heavy equipment could be some of many stumbling blocks that face the deployment of IIoT in the industrial field. However, the requirements and their necessity vary according to the application. The following are few examples of those harsh industries and their specific needs.

- **Mining production**

  Mining is a harsh environment due to the potentially toxic atmosphere in the underground mine, besides, the large, heavy and dangerous equipment and the ever-present possibility of an emergency situation. Here the IoT technology is required to ensure the safety of the workers working in the mines [16] and to track the manufacturing process. It is also essential to monitor any unexpected situation as any failure in that system will cost the company. However, there are still some power issues as most of the mining is in remote areas. Also, the deployment of wireless sensor networks in mining environments face high levels of signal interference because of the metallic objects around.

  Therefore, IIoT applications deployed in any mining facility must be able to handle interference, support long ranges and have extended battery lifetime.

- **Construction Industry**

  IoT can also play a significant role in construction operations. Places, where constructors cannot proceed with their work due to weather conditions or poor air quality from pollution, is an example in which remote operation could take place. Tracking the tools and equipment onside will help to locate each item efficiently and quickly and help in monitoring the constructing process. Moreover, labeling the supplies with RFID tags can assist in counting the supplies on the project and trigger a notice when inventory is low. Tracking inventory enhances the construction system and reduce the cost of waiting for supplies and of unused supplies [17].

  Therefore, an efficient tracking technique must be adopted. Hence, the data transfer between the sensor nodes has to be acknowledged instantly to detect and avoid any wrong situations happening in the system.

- **Firefighting**

  In any industrial or manufacturing field, the probability of having a fire due to system failure or individuals' behavior increases. IoT is used for safety and fire-fighting [18]; by using sensors to detect the behavior of the fire, its intensity and direction to provide early warning alarms to prevent calamities and succeed rapid response and rescue.

  A primary requirement in such application is the ability to support minimum waiting time between the transmission reported data. Hence, assuring the efficient monitoring of any smoke or fire.

In addition to the previous requirements, in certain situations, there might be a need to send an urgent command for the deployed sensor node to take a specific action or behavior. Thus, in such fields, a broadcasting feature would be essential to be supported. In summary, the highlighted requirements for the harsh IIoT are:

1- Low waiting time: to be always updated with the process and to avoid any unwanted situation during the operation of the system.

2- Acknowledging every packet: to reach efficient tracking and monitoring for real-time applications.

3- Long range: cover wider areas with fewer sensor nodes.

4- Extended battery lifetime: avoid the frequent need for batteries charging or replacement.

5- Supporting broadcasting: could send command messages in urgent situations.

We remark that in many harsh applications do not require networks with a large number of nodes. For instance, in the mine in [19], only 18 sensor nodes are required per system. The food supply chain

represented in [20] was designed with 16 sensor nodes per one BS. Therefore, often only a limited number of nodes is required.

2.2 The Physical Layer

The PHY layer is where the communication starts, and it is responsible for the data transmission. In addition, it converts the signal from one form to another so that it can be transmitted over a communication channel. The modulation technique of the signal plays a significant role in its range of communication and its exposure to interferences.

One of the significant PHY layers that have been developed and studied extensively is LoRa. LoRa is a Low Power Wide Area (LPWA) technology that offers long range, low power and noise free communication [21]. The unique part in LoRa is its modulation technique, enabling it to achieve longer ranges compared to other modulations.

For instance, the Frequency Shift Keying (FSK) operates above the noise floor in a narrow band and can be easily stepped down with the noise or with other signals. LoRa uses Chirp Spread Spectrum (CSS) modulation which achieves long range communication with the ability to decode transmission 20 dB below the noise floor with higher sensitivity [22]. Compared to Zigbee, LoRa can reach extended ranges with lower energy consumption by using lower frequency operation which is spread out to consume less energy. However, the low frequency transmissions will be translated to low data rate. But, it is rarely for the IoT applications to require significant data rate. Thus, LoRa is suitable to be used in the IIoT fields. In our work, we highlight LoRa illustrating how it operates and its features.

2.2.1 LoRa

LoRa is the PHY layer designed by SEMTECH [23] for IoT applications. Many studies showed the significant potential of LoRa especially when it comes to industrial wireless networks [7]. LoRa is a long-range wireless communication system that uses low power and low communication data rate. On top of LoRa's physical layer, there are some MAC protocols such as LoRaWAN, Symphony Link, and MAC on

Time (MoT). We illustrate LoRa PHY layer and explain its parameters and frame structure, followed by the MAC layers used on top of LoRa PHY layer.

2.2.1.1 LoRa overview

The radio chip of LoRa modulates using the chirp spread spectrum (CSS) technology [24]. CSS encodes the information using frequency chirps with a linear variation of frequencies over time. CSS has been used in military and space communication for decades, due to the long communication ranges and its robustness against interference. **Figure 2-1** shows the LoRa modulation over time [25].

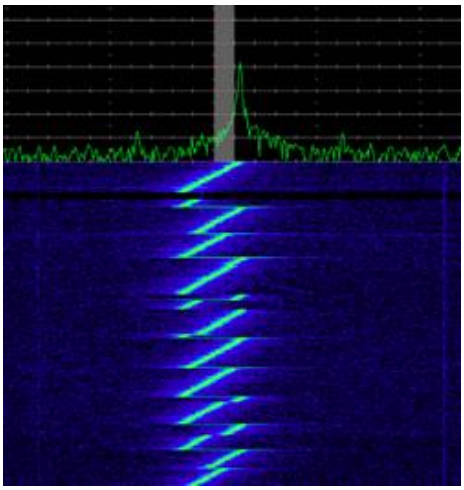

Figure 2-1: The LoRa Chirp Modulation over time
(Reproduced from [25])

LoRa uses the unlicensed Industrial, Scientific and Medical (ISM) radio bands and operating frequencies which vary by region and transmits with a data rate of up to 50Kbps in the ideal environment [26]. Semtech claims that LoRa's battery life can last up to 20 years [23] which makes it an excellent solution for many applications.

2.2.1.2 **Parameters and Frame Format of LoRa**

There are several parameters that customize LoRa modulation which makes it unique: Spreading Factor (SF), and Bandwidth (BW). These two parameters profoundly affect LoRa's modulate bitrate, the

maximum coverage and its resistance to the noise. LoRa CSS modulation using multiple spreading factors SF ϵ {7, 8, 9, 10, 11, 12} to cover broader areas and uses that SF to define the number of chirps per symbol, as 2^{SF} chirps refer to a LoRa symbol. The bandwidth in LoRa is equal to the chirp rate. Therefore, the effect of changing the SF will reflect on the frequency spread and the symbol duration. There is always a trade-off when it comes to choosing the SF and BW, by increasing the bandwidth results in a higher bitrate however that lowers receiver sensitivity. Whereas by increasing the SF results in better sensitivity and longer ranges, however, reduces the bitrate. Table 2-1 shows the effect of SF and BW on the sensitivity [23].

SF / BW	6	7	8	9	10	11	12
125 kHz	-118	-123	-126	-129	-132	-134	-137
250 kHz	-115	-120	-123	-126	-129	-131	-134
500 kHz	-112	-117	-120	-123	-126	-128	-131

Table 2-1: The receiver sensitivity in dBm at different BW and SF using LoRa Calculator Tool

Regarding the frame structure, LoRa packet can be concluded in three main chunks: Preamble, Optional Header and Payload, Figure 2-2 illustrates the structure of the frame. LoRa's modem uses two kinds of formats for its packet, explicit and implicit; the difference between them is that in the explicit format the header is included after the preamble.

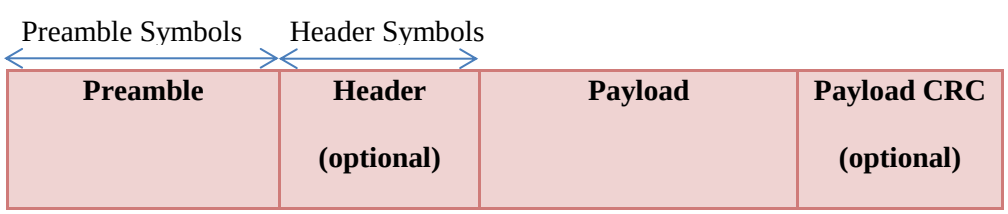

Figure 2-2: LoRa Packet structure

- **Preamble**

The preamble is used to do the synchronization between the transmitter and the receiver with the incoming data flow, making sure that the receiver is ready to receive the data. The preamble length is programmable and can be changed depending on the application. Having an extended preamble is useful for the asynchronous protocols which reduce the idle listening and also assure high delivery ratio. However, more extended preamble will cause a high level of energy waste, overhearing and latency. Choosing the preamble length will depend on the network and how intensive it is [23].

- **Header**

There are two header modes: explicit header mode and implicit header mode. Explicit header mode enables the presence of the header which provides some information about the incoming payload such as the payload length and indicates the presence of the optional CRC at the end of the frame. Sometimes when information about the payload is fixed and known in advance, it is useful to remove the header by activating the implicit header mode. Hence, saving some transmission time which will lead to saving energy [23].

- **Payload**

The payload is the actual data needed to be transmitted from the source to the destination; it is a flexible value that can be adjusted depending on the amount of data with a maximum of 255 bytes [23].

Therefore, it is apparent the significant role that LoRa can take in achieving many of the industrial requirements. Authors in [27], [28], [29] discuss examples of adopting LoRa in the industry in three different applications: wide stores control, noisy environments, and patient monitoring, respectively. However, having a significant physical layer is not enough without a robust MAC protocol to manage the communication.

2.3 LoRa Based MAC Protocols

MAC protocols are responsible for managing the traffic between the nodes, and they control the radio operations inside the node. Thus, the design or the choice of a MAC protocol for a particular application is very important. The protocol should reduce the power consumption, handle heavy traffic, and avoid collisions. Therefore, the decision for the MAC protocol designed can be highly effective in the performance of the system. We will divide the MAC protocols that run on top of LoRa according to their channel access method into contention-based protocols and scheduling-based protocols.

2.3.1 LoRa Contention-based MAC Protocols

Contention-based protocols are the earliest protocols to be developed for most wired and wireless systems, mainly used in the Ethernet and IEEE 802.11 WIFI family [30]. They allow any node to access the channel as there is no prior coordination among the nodes. When a node has a packet to send, it transmits at the full channel data rate which can easily result in collisions when two or more nodes try to send packets across the network simultaneously.

The main challenges in the random-access protocols would be how to detect collisions and how to overcome them. LoRaWAN is a contention-based MAC protocol was designed to work with LoRa PHY layer.

LoRaWAN

LoRa's official implemented MAC layer is LoRaWAN which mainly uses Additive Links On-line Hawaii Area (ALOHA) traditional protocol [31]. The network's architecture for LoRaWAN can grossly fall into four parts: the end devices, Gateways (Base Stations), network server, and the application server. LoRaWAN network is a hybrid network that groups multiple communication technologies. For instance, the connection between the end devices and the gateways uses LoRa communication. However, the connection between the gateways and the server uses an IP backhaul interface, such as LTE or Ethernet. LoRaWAN categorizes the end

devices into three different classes for different applications [21]. The data sheet [21] provides more information of LoRaWAN protocol.

Semtech claims that LoRa's battery life can be up to 20 years, but many studies assumed that this could only happen in a meager transmissions rate (one transmission per day or several days) [32]. Furthermore, the contention-based property in LoRaWAN makes it more prone to collisions thus leading to delays [9]. In addition, LoRaWAN is not entirely opened for developers; therefore, adjusting it is not possible.

2.3.2 LoRa Scheduling-based MAC Protocols

Scheduling protocols aim to divide the full frame into smaller slots; each slot is assigned for one node to access the channel. Scheduled MAC protocols generally use their synchronization techniques to minimize the collision as each node can only use the channel in its scheduled time-slot.

By having a well-designed scheduling protocol, many of the industrial difficulties could be eliminated. Collisions if not excluded can be minimized, achieving high delivery ratio used for tracking applications. Moreover, the fairness is obtained in such protocols as each connected node is guaranteed its share from the frame. Also, adding or removing nodes will not affect the channel or any parameters, which will improve the scalability opportunities. Finally, the energy consumption can be reduced significantly by reducing the time in which a node stays active as a node will only get active during its time-slot. Therefore, the scheduling protocols are more suitable for industrial applications than the contention-based protocols [34].

There are two scheduling LoRa based MAC protocols namely, Symphony Link and MoT.

Symphony Link

Symphony Link is a centralized scheduling protocol that uses LoRa. It is a commercial company founded in 2014 by a group of engineers from Johns Hopkins University. They are specialist in LPWAN technology for IoT devices for applications such as; industrial tracking, area monitoring, and inventory management. According to the official website [35], Symphony Link claims better performance over LoRaWAN in specifications such as; power efficiency as they use solar cells, cost, and spectrum usage. However, to the best of our knowledge, Symphony Link techniques and breakdown is not available in the literature.

MAC on Time (MoT)

MoT is a new designed MAC protocol over LoRa PHY layer which uses a centralized synchronization technique [36]. MoT has been designed to be suitable for different industries. Compared to LoRaWAN, MoT achieved less waiting times with higher throughput and longer lifetime. MoT is a centralized MAC protocol where there is a base station (BS) or a gateway responsible for handling the synchronization between the network nodes. The gateway used in MoT is a multiple channel gateway, giving it an advanced feature in supporting a large number of nodes. MoT is a hybrid protocol that combines the contention-based on one channel (connection channel) and Time Division Multiple Access (TDMA) based on the other channels (reporting channels).

The gateway in MoT divides all the channels into reporting phase and connecting phase. The reporting phase then is divided into time-slots and the time-slots into sub-slots. The sub-slots are where the nodes send their packets. MoT offers a collision-free channel through accurate calculation for the sub-slots used by every node, as each node is allowed to transmit its data only at its sub-slot. After every full time-slot, the gateway acknowledges receiving the nodes' packets.

In Mot, the nodes are only allowed to connect to the network through the connection channel. Every node gets a different slot from the gateway to transmit its data. Hence, it achieves a lower delay and longer lifetime due to the elimination of collisions. In every sub-slot, a node transmits its data to the gateway or the BS towards the back-end and then to the devices as shown in Figure 2-4.

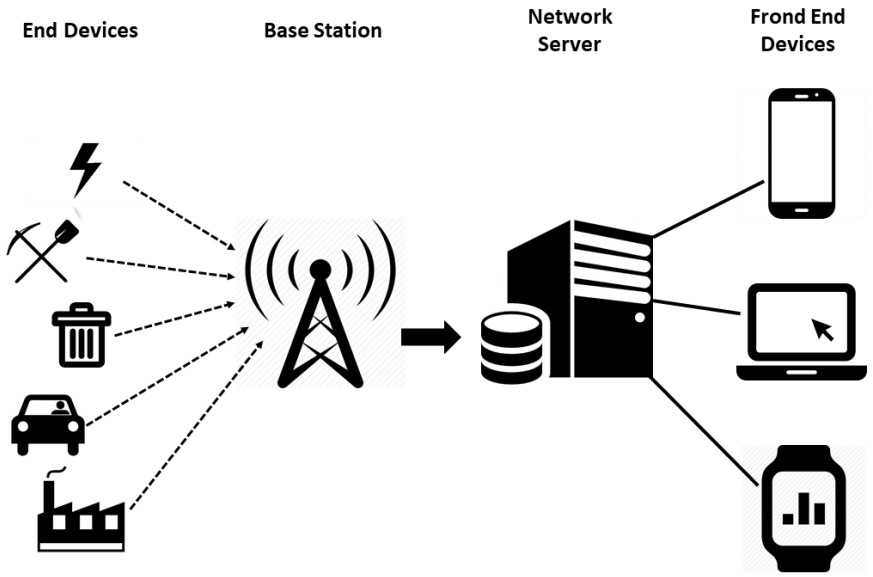

Figure 2-3: MoT Network Architecture

According to [36] MoT shows great improvement compared to LoRaWAN regarding lower delays and high throughput. However, few things in MoT can be adjusted to make it suitable for the IIoT harsh applications.

The IIoT applications require fast acknowledgment of the transmitted packets to realize better monitoring. In MoT the acknowledging of the packets happens after a full time-slot, leading to inefficient tracking which is considered one of its major drawbacks. In addition, the MoT frame does not include downlink duration in which the gateway can send necessary commands to the nodes. Furthermore, MoT obtains large networks up to 1000+ nodes, but on the other hand, it

adds complexity and hardware cost for its gateways: generally, in most cases, IIoT applications do not require that many nodes.

In conclusion, LoRa PHY layer showed significant potential for adopting the IIoT industries. The contention-based protocols above LoRa are not suitable for the industrial application due to their high collision rates. Besides, they are generous in the energy consumption caused by the multiple retransmissions which are due again to the high collision rate.

On the other hand, the centralized scheduling as in MoT represents a collision-free medium with high throughput and minimum delays. The main pros for the centralized scheduling is the ability to reduce the energy consumption as the nodes do not have to stay listening or transmitting for long period, besides, the hidden terminal issue does not exist. In addition, the centralized feature makes the network easier to be scalable as nodes do not rely on one another. However, in that fashion of scheduling if the sink node fails the system goes down and the peer-to-peer communication is not possible.

In general, IIoT applications, MoT will be well suited. However, it needs modification to be suitable for the harsh industrial applications. In the next chapter, we introduce SC-MoT, which is a modified version of MoT with a single channel of communication. SC-MoT aims to modify MoT to make it convenient in the harsh IIoT applications.

Chapter 3

SC-MoT: Single Channel MoT

Although MoT showed promising results for reducing the industrial dilemmas, by having low delays with low energy consumption, it has to be adapted for use in the harsh IIoT applications. SC-MoT aims to adjust MoT to achieve lower waiting times and better energy consumption while maintaining the primary features of MoT.

We first demonstrate our design goals and requirements to adjust MoT, followed by an overview of how SC-MoT works and its main features. Next, SC-MoT will be broken down into more details showing its design and calculations.

3.1 SC-MoT Design Goals

1- ***Acknowledging every packet***

One of the main drawbacks in MoT is not acknowledging every report packet. The base station (BS) in MoT transmits acknowledgments after every time-slot in which it receives multiple of reports packets. Hence, causing delays which will affect the performance of the system, leading to inefficient tracking. In critical industries, many applications need an accurate tracking system to be able to monitor any failure in short time. Hence, acknowledging every packet is a top priority in the IIoT applications.

2- ***Support downlink***

Many protocols focus on collecting the data from the deployed nodes through uplinks (UL) periods without considering the downlink (DL) period. MoT is no exception as it only supports uplink transmission and the DL is only used in acknowledging the received packets. Thus, the broadcasting from the (BS) to the nodes is not supported. However, in many applications, there are needs to broadcast commands to the network's nodes for a specific task or urgent situations.

Also, having a DL period will help in supporting the over the air (OTA) programming; where the BS can assign new tasks or adjust the nodes assignment by broadcasting it during the DL period. In SC-MoT we consider having an optional DL period used whenever needed whether to broadcast command messages or for the OTA programming. Moreover, having one channel makes it easier to broadcast messages to all the nodes in the network, unlike MoT that even in case of broadcasting must happen once on each channel.

3- A Limited number of nodes

One of the significant MoT's advantages is the ability to support a massive amount of nodes up to 1000 nodes. Therefore, MoT was designed with multiple channels to have the capability to cover that number of nodes. However, many of the IIoT applications only have a few nodes in their networks. SC-MoT is designed to support a limited number of nodes up to 250 nodes. Hence there is no need for having multiple channels.

4- Long Lifetime

Replacing new batteries in harsh industrial nodes is a hard task and even might be impossible in some applications. MoT succeeds in achieving long lifetime up to multiple years even longer than LoRaWAN according to [9]. Therefore, having long lifetime nodes is a bottleneck in many applications. In SC-MoT we aim to improve the lifetime of the nodes.

5- Low waiting time

In many harsh applications, a node is required to frequently transmit to keep a right track and to achieve its assign duties efficiently. MoT was designed with accurate calculations to make it possible to reduce the waiting time as low as 5.7 seconds. The waiting time is the minimum time a node has to wait before transmitting the next packet. One of the advantages of MoT is the ability to maintain low waiting times when the number of nodes is high. Since our target systems

will only have a limited number of nodes, we select to use a single channel. We argue that SC-MoT is capable of reducing the waiting time, hence obtaining better tracking performance.

3.2 SC-MoT Overview

SC-MoT is modified design for the MoT protocol which has been created to overcome several problems in the MAC protocols and to reach a “good” solution for most of the IIoT needs. SC-MoT aims to eliminate the industrials hitches by having a robust protocol that ensures; extended communication range, long Life-time and low waiting time with the support of DL periods and acknowledging every packet. Like MoT, SC-MoT is a centralized synchronous protocol based on TDMA scheduling, and it uses LoRa physical layer for its modulation advantages.

SC-MoT design is mainly for the applications that need multiple nodes to serve one main purpose specifically for the harsh IIoT applications. LoRa is used for SC-MoT to gain; extensive coverage, lower transmitting power and reduce the noise interference. SC-MoT uses a single channel for all the communication and packets transfer.

MoT has a separate connection channel where the nodes initially connect to the network. Unlike MoT, in SC-MoT the connection of the node will happen on the same channel by dividing the frame into two phases namely, connecting phase and reporting phase. Each node in the network will first connect to the network through contention-based connection phase. Followed by reporting phase, where each node connected to the network will have a collision-free time-slot to use for its transmitting. In addition, an optional downlink period can be added to the frame if needed.

SC-MoT is a hybrid protocol where each frame will consist of a contention-based phase, followed by scheduled phased based on TDMA. SC-MoT uses star topology architecture, and it is centralized protocol. Thus there is a centralized base station or a coordinator responsible for managing the scheduling in the channel and assigning the time-slots. The information is then forwarded to the back-end server, up to the front-end devices. An acknowledgment is required to be sent from the base station back to the node to confirm the arrival of each packet. SC-MoT uses the same network architecture as MoT, which

illustrated in Figure 2-4. The following sections will carry an itemized discussion on SC-MoT, how it works and the modeling design.

3.3 SC-MoT Breakdown

SC-MoT was designed with high accuracy to reach the industrial expectations and to overcome IIoT problems. In this section, we describe SC-MoT and demonstrate the adjustment made on MoT. Starting with the frame structure, passing through the messages exchanged between the BS and the nodes, reaching to the operation and calculations used in SC-MoT.

3.3.1 SC-MoT Frame Structure

SC-MoT is centralized protocol; the base station is the one coordinating the channel access time-slots. The base station divides frames into two phases; *Connection Phase* and *Reporting phase*. However, the *Downlink phase* can be optionally added to any frame by the base station. As there is only one channel available in our protocol, so we need to assure there are no collisions between the connecting nodes and the reporting ones. That is achieved by broadcasting *PhaseChangePacket* (PC_P) at the beginning of each phase to separate the two phases. This packet is used to inform any listening nodes about the phase starting. The packets functions and frame structure will be illustrated in detail in subsection 3.3.2. Figure 3-1 shows a basic scheme of the SC-MoT frame and the two phases. The two phase's duration is dynamical; changes according to the number of nodes connected to the network and according to the frame size. At the beginning of the network, the whole frame would be connection phase, however by more nodes connected to the network, the connection phase will shrink, and the reporting phase will extend as shown in Figure 3-2. Hence, that will give us the capabilities for efficiently assigning DL when needed.

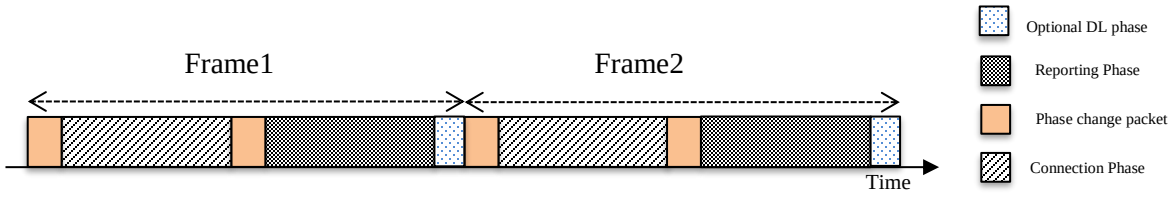

Figure 3-1: SC-MoT basic frame structure

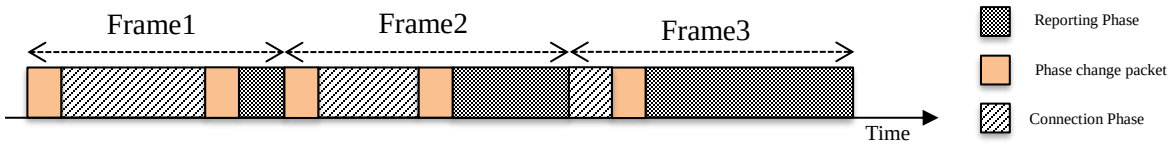

Figure 3-2: SC-MoT Dynamic Frame between the two phases

3.3.2 SC-MoT Messages Types and Their Packet Structure

There are different types of messages types used by SC-MoT; each message has a specific function, packet size, and packet structure. The first 8-bits of any of those packets are fixed to the packet's name followed by the specification of the packet, depending on its type. The packets are illustrated below.

1- **Phase change Packet *(PC_p)*** the PC_p is broadcasted from the base station to the nodes; it is used to inform the unconnected nodes about the starting of the connection and reporting phases. PC_p switches between the connection and the reporting phases as in MoT each operating happens on a different channel. PC_p is 10 bytes, divided as 1 byte for the packet type, 6 bytes for the base station MAC address which is the source in this situation, 1 byte for the phase to start whether it is connecting or reporting, and remaining 2 bytes for the duration of that phase *(T_p)*. Figure 3-3 shows the PC_p.

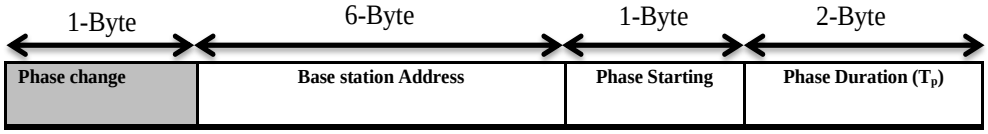

Figure 3-3: Phase change packet

2- **Connection Request packet *(CR_p)*** This packet is sent from the node to the base station during the connection phase to join the network. When the unconnected nodes receive from the base station the *PCp* mentioning the starting of the connecting phase, they wait a random time between the phase duration then send the *CRp* to the base station. The *CRp* is 15-bytes in total divided as, 1 byte for the message type, 6 bytes for the node address (source). In addition, 6 bytes for the base station address (destination), followed by 1 byte for the payload size (PL) that the node will be sending and 1 byte for the packet ID, see Figure 3-4.

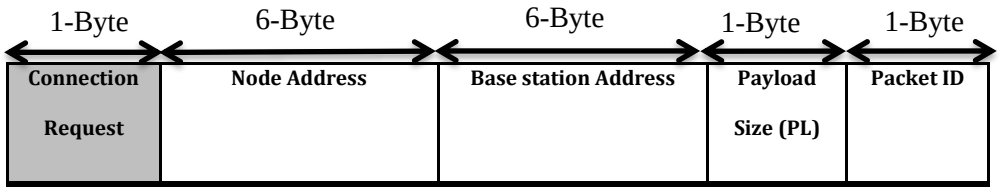

Figure 3-4: Connection Request Packet

3- **Connection Approval and Connection Denied Packets *(CA_p) and (CD_p)*** with a 17-bytes and 13 bytes for the connection approval and denial respectively, the base station will answer the node request to join. For the *CAp*, besides the message type and the source and destination addresses, a short address of 2 bytes is given to each node to use while reporting to reduce the reporting packet size. The short address is unique for each node. The last 2-bytes will carry the time-slot (TS) scheduled for the node to access the channel according to its index. The *TS* is the number of seconds/minutes the node will wait before getting active and transmitting. In some situation, for instance, unauthorized node or full capacity the base station will send *CDp* consist of the message type and the two addresses only. In such cases, a node has to try connecting later. Each connected node will have a consecutive index stored at the BS. Figure 3-5 and Figure 3-6 shows *CAp and CDp*, respectively.

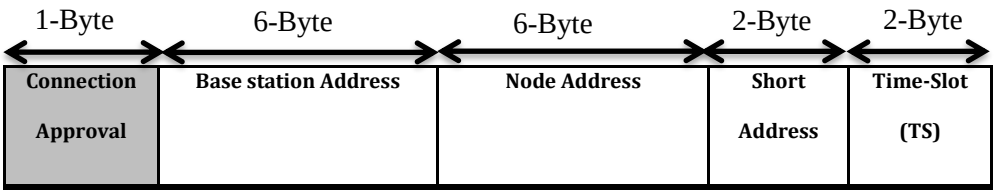

Figure 3-5: Connection Approval packet

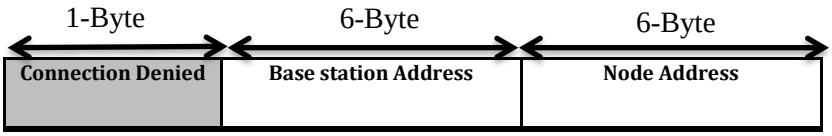

Figure 3-6: Connection Denied packets

4- **Report Packet *(R_p)*** is the periodic packet to be sent from the node to the base station during the reporting phase. Nodes connected to the network will transmit their packets in the scheduled time-slots. The R_p size will depend on the payload size in the report message. An important point to mention that the destination address (Base station) is not required in the R_p as the Base station will be the only end receiving the packets and any other node will ignore it. Thus, the packet will consist of a message type, the 2-bytes short address assigned, payload and the 1-byte packet ID Figure 3-7.

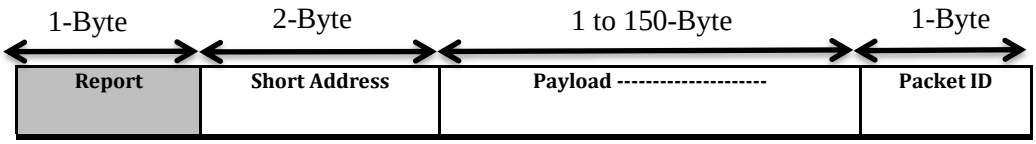

Figure 3-7: Report Packet

5- **Acknowledge and Not Acknowledge packets *(A_p) and (NA_p)*** One of the primary design requirement is to acknowledge every received report for better tracking application in IIoT. The acknowledgment packets are sent from the BS back to the node after receiving the *Rp*. The *Ap* is 9-bytes will carry the message type, the short address of the destination node, the next time-slot

for the node to send the report, the packet ID and a 2 byte for the *DL*. The 2 bytes for the DL indicating whether there is a downlink phase in this frame or not. In case of *DL*, this packet will also send another time-slot for the nodes to receive the broadcasted message.

However, sometimes the base station might receive a corrupted report in such case the base station will send *NAp* (5-bytes) which only have the type of the message, short address and the time-slot for the next report. We assure to send a NA_P to segregate having a corrupted packet from any other failure. The Figure 3-8 and Figure 3-9 shows the A_p and the NA_p.

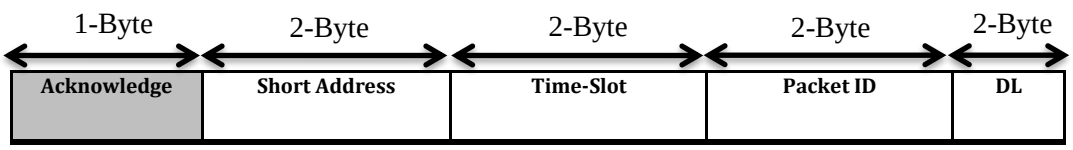

Figure 3-8: Acknowledge packet

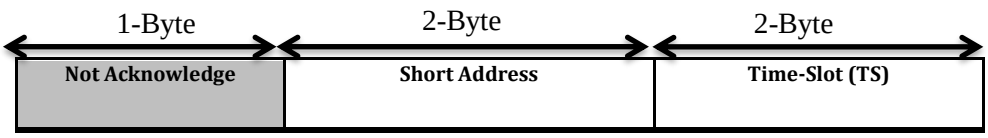

Figure 3-9: Not Acknowledge packet

6- **Downlink packet *(DL_P),*** Another main feature in SC-MoT, is the downlink support. During some frames, the BS will need to broadcast some command messages to all the nodes. Such broadcasting will happen through the DL_P. The DL_P will be divided into three parts; the message name, the base station address and the command message. In our design the command messages will be fixed to 20-bytes, hence the DL_P 27-byte overall. Figure 3-10 shows the DL_P structure.

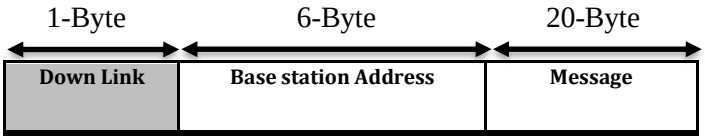

Figure 3-10: Down Link Packet

3.3.3 SC-MoT Operation

We can now discuss the sequence of the operation during each phase (Connecting / Reporting / Downlink).

A. **Connecting Phase:** The connection phase is the duration where the unconnected nodes can join the network. In SC-MoT the connection phase is a contention-based phase where nodes connect to the network using the traditional ALOHA protocol [31]. Nodes will wait in the *ReceiveMode (RxMode)* to listen to the PC_p of the starting of the connecting phase. Once receiving it by the nodes, they wait a random time between 0 and T_p (duration of the phase) and send their CR_p to the BS; requesting to join the network and get a scheduled time-slot (*TS*). The random time waited is used to reduce the collision probabilities between the requests.

   The BS then will receive the request and send the CA_p *or* CD_p back to the node. The *TS* in which the node will get active and transmits its packet will be inside the CA_p. Later in the chapter, the calculation of the time-slot will be illustrated. Once the node receives the CA_P, it switches to the *SleepMode* until the scheduled *TS* to send the R_P which will that happens in the reporting phase.

   Another advantage of SC-MoT over MoT is the quick response from BS to the connected nodes. As in MoT a node sends its connection request packet on the connection channel and waits in the *RxMode* until requests approval phase. Such time can dramatically increase in big networks leading to energy loss. The flowcharts in the Figure 3-11 show the basic operation of the node and the BS during the connecting phase.

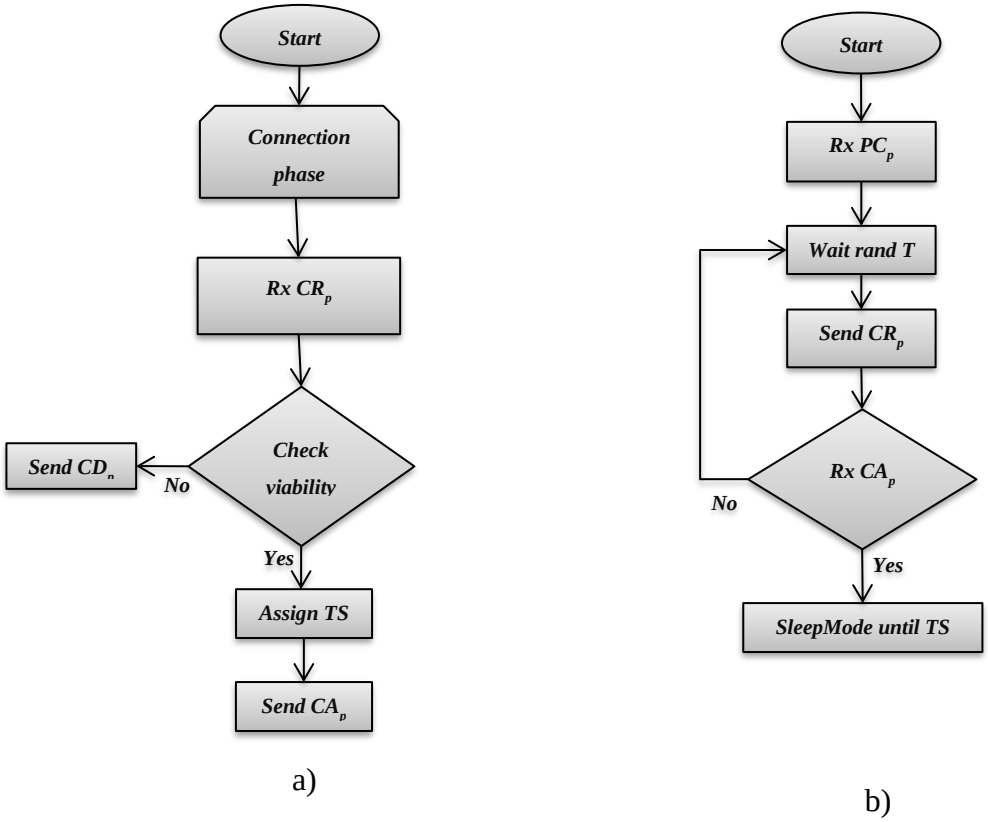

Figure 3-11: Flowchart for the connection phase a) Base Station b) Node

B. **Reporting Phase:** During the reporting phase all the connected nodes that have a scheduled *TS* will *wakeup* only in their *TS* and transmit their R_p followed by waiting time to receive the A_p from the BS. The nodes will do that respectively according to the *TSs* scheduled. The reporting phase is a collision-free phase as no nodes will transmit their reports at the same time. The flowcharts in the Figure 3-12 show the basic operation of the node and the BS during the reporting phase.

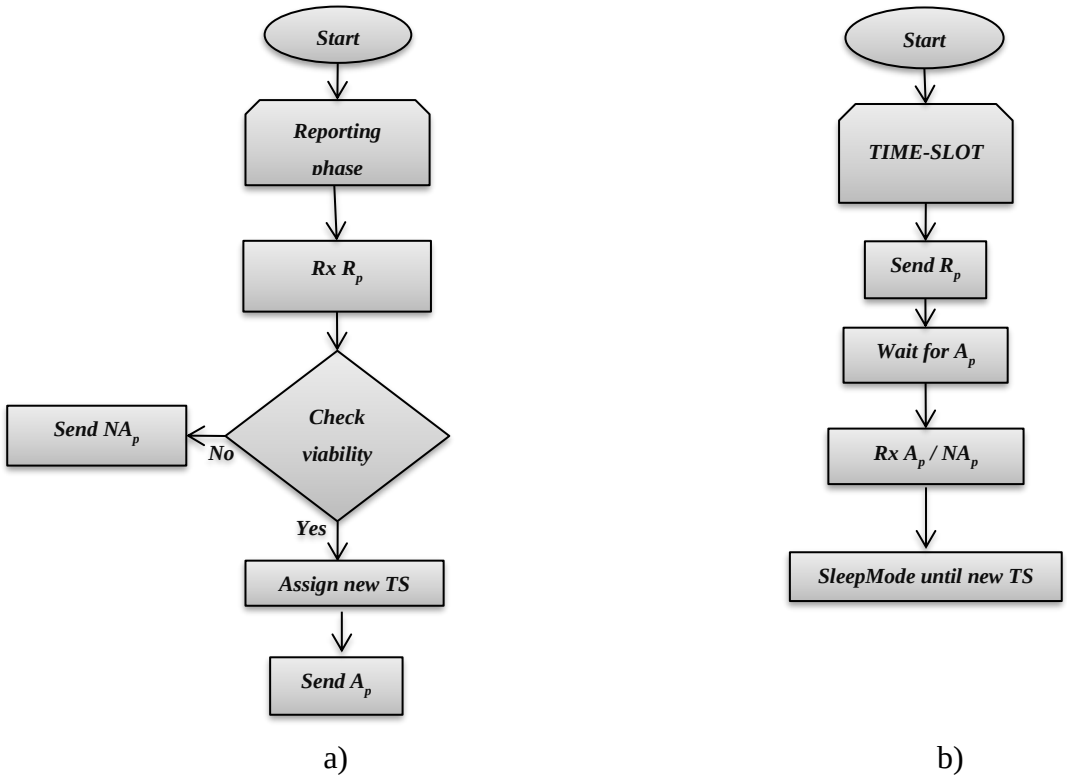

Figure 3-12: Flowcharts for the reporting phase a) Base station b) Node

C. **Downlink Phase:** In case of downlink phase, the BS will inform the nodes of the upcoming downlink in the A_P. The nodes will *wakeup* all at the same time given from the BS to Rx the DL_P. After receiving the DL_P, the nodes will go again into the *SleepMode* and continue the typical sequence. The flowcharts in the Figure 3-13 show the basic operation of the node and the BS during the Downlink phase.

From Figure 3-14 we can back up the packets transferring throughout the frame time during the three phases.

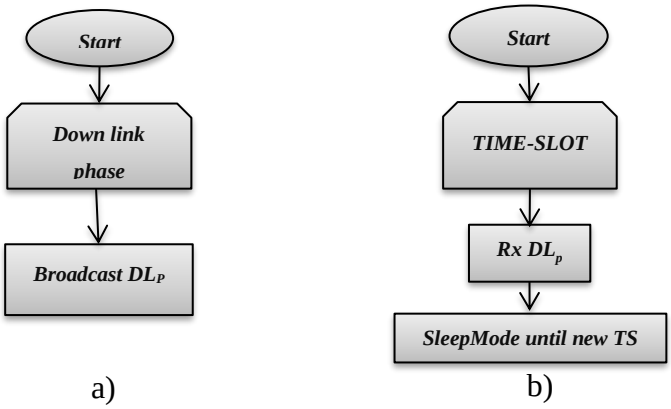

Figure 3-13: Flowcharts for the Downlink phase a) Base Station b) Node

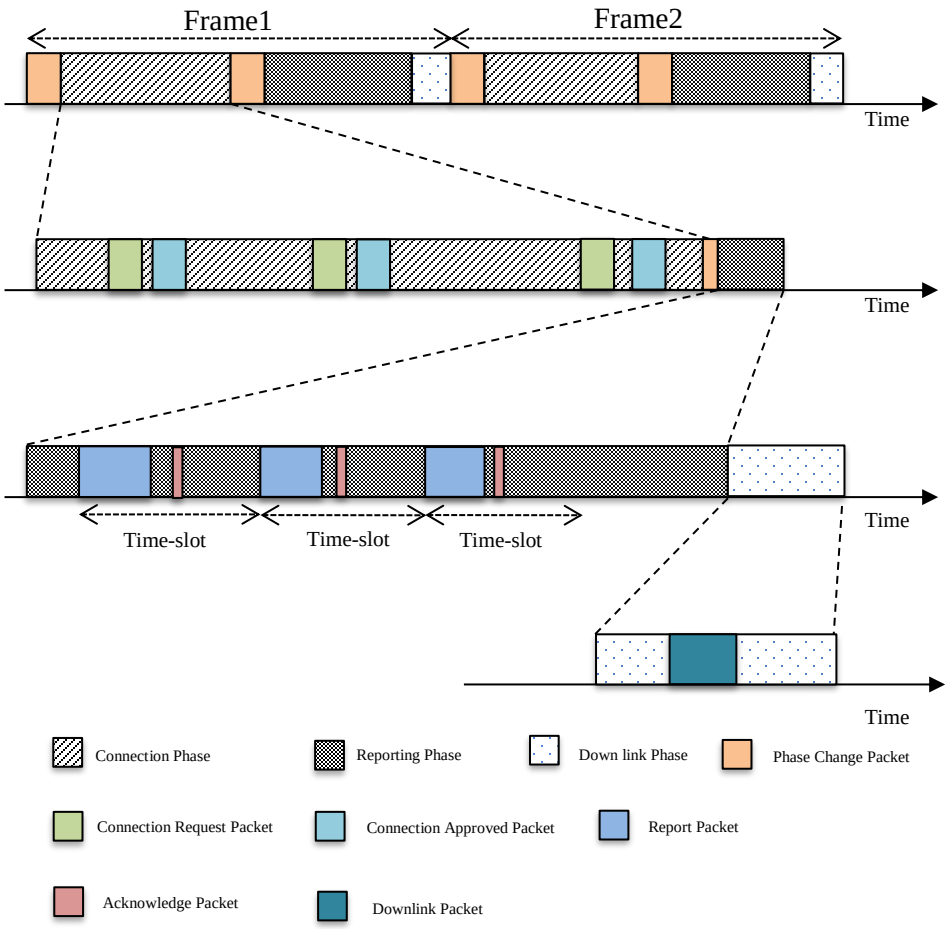

Figure 3-14: SC-MoT packets operation throughout the frame

3.3.4 SC-MoT Time Handling and Scheduling

To reach the targeted design goals and to reduce the waiting time, accurate timing calculations are required. The timings that play a considerable role in SC-MoT are, the duration of one time-slot (TS), the length of each phase, connecting and reporting, *(D_{CP} and D_{RP})*, and the time until a time-slot restart. Duration of the downlink D_{DL} phase will also be calculated as well, however, it is not a major part of the protocol calculations.

1) **Duration of one Time-Slot *($D_{Timeslot}$)***

   The duration of any time-slot mainly depends on the time on air *(T)* of any packets transferred during that slot. Since each time slot consists of R_P and A_P, we calculate the *T* of each packet with some tolerance *(Tol)* value between the packets to compensate any clock drifts would appear.

   T_{Rp} will change depending on the payload size of the report; however, the T_{Ap} will be constant for all the reports. Equation (3.1) shows how SC-MoT calculates the duration of the time-slot.

   We also calculate in Equation (3.2) the duration needed in connecting one node *($D_{connecting}$)* using the *T* of the CR_p and the CA_P. The Time on Air *(T)* calculations can be found in LoRa datasheet [23].

$$\boldsymbol{D_{Timeslot_i} = \left(T_{R_{P_i}} + T_{A_P}\right) * Tol} \qquad \textbf{(3.1)}$$

$$\boldsymbol{D_{connecting} = \left(T_{CRp} + T_{CAp}\right) * Tol} \qquad \textbf{(3.2)}$$

2) **Duration of DownLink Phase *(D_{DL})***

   In some cases when there will be a downlink phase in the frame. The BS station will inform the nodes with an additional time inside the frame to get active and receive some command messages.

The duration of that *DL* phase will depend on the message PL size as in the calculation of the $D_{Timeslot}$. Equation (3.3) shows the D_{DL} calculation depending on the *T* of the DL packet (T_{DLp}) and some *Tol* value.

$$\boldsymbol{D_{DL} = T_{DL_p} * Tol} \qquad \textbf{(3.3)}$$

3) Duration of Reporting and connecting phases *(D_{CP} and D_{RP})*.

The phases' duration will be calculated every time new node join or leave the network. The length of each phase will depend mainly on three parameters; the number of nodes already connected *(n)*, the frame size *(FS)* and duration of one TS ($D_{Timeslot}$). The FS is the full duration of all the phases in the frame and it is a fixed value for a network with a certain number of nodes. It depends on the number of nodes and how frequent the nodes should transmit. Equation (3.4) and Equation (3.5) show the calculations of the duration of each phase.

$$\boldsymbol{D_{RP} = \sum_{i=0}^{n_{nodes}} D_{Timeslot_i}} \qquad \textbf{(3.4)}$$

$$\boldsymbol{D_{CP} = FS - D_{RP} - D_{DL}} \qquad \textbf{(3.5)}$$

4) The time until the time-slot starts and restarts *(TS)*

The *TS* is sent in the *Connection approval packet* or the *Acknowledge packet.* By *TS* we mean the time the node will wait before transmitting, we can think about it as a countdown before using the channel. Similar to MoT, this technique was used to overcome the issue of most of the TDMA protocols which is the clock-drift that is caused by having a global time clock that has to be resynchronized between the different nodes in the network [37]**.** Therefore, MoT and SC-MoT do not require clock synchronization between the nodes and the BS.

The *TS* for each node will also be calculated each time the BS receives a *report* from the node, as the frame could change if any node has been added or removed from the network. The *TS* is then

included in the acknowledge packet. The index *(i)* assigned for each node will be used in the calculations assuring privation of the overlapping.

To calculate the *TS* for a newly connected node, we first calculate the remaining time in the connection phase (rD_{CP}) through Equation (3.6) which will use the duration of connecting $(D_{connecting})$ and the time already passed in the connecting phase $(T_{Cpassed})$. Then we calculate the first time slot (TS_n) using Equation (3.7), the TS_n is included in the *Connection Approval packet* in case a new node is connecting.

On the other hand, Equation (3.8) calculates the time remaining in the reporting phase (rD_{RP}) using the time already passed in the reporting phase $(T_{Rpassed})$ and the duration of acknowledgment packet (D_{Ap}). Equation (3.9) calculates the *TS* that will be included in the *Acknowledge packet* to inform the node how long to wait before the next slot.

$$\boldsymbol{rD_{CP} = D_{CP} - \left(T_{Cpassed} + D_{connecting}\right)} \qquad \textbf{(3.6)}$$

$$\boldsymbol{TS_n = rD_{CP} + (D_{Timeslot} * Slot_{i-1})} \qquad \textbf{(3.7)}$$

$$\boldsymbol{rD_{RP} = D_{RP} - \left(T_{Rpassed} + D_{Ap}\right)} \qquad \textbf{(3.8)}$$

$$\boldsymbol{TS = rD_{RP} + D_{DL} + D_{CP} + (D_{Timeslot} * Slot_{i-1})} \qquad \textbf{(3.9)}$$

$\boldsymbol{D_{Timeslot}}$: Duration of TS

$\boldsymbol{Slot_i}$: the slot index referring to the position of the time slot inside the reporting phase, assuring collision-free transmissions. Every node will wait until the nodes in the previous slots transmit then access the channel. The initial value of *(i)* is assumed to be 1.

3.4 Energy Consumption in SC-MoT

SC-MoT aims to reduce the energy consumption. Similar to MoT, SC-MoT uses LoRa modulation which is one of the leading technologies on LPWAN due to its ability to achieve broad coverage with low transmitted power [23]. On the other hand, the centralized scheduling manages to minimize the time in which the nodes are active in it by adopting long *sleepmode* time for each node during the frame size. A node will go directly to *sleepmode* after receiving its time slot *TS* from BS in every A_p. That gives the nodes more time in the *sleepmod*e which profoundly reduce the energy consumption as the only time a node will be active is only during the time-slot scheduled for it. Figure 3-15 shows the consumption pattern of SC-MoT during the three phases.

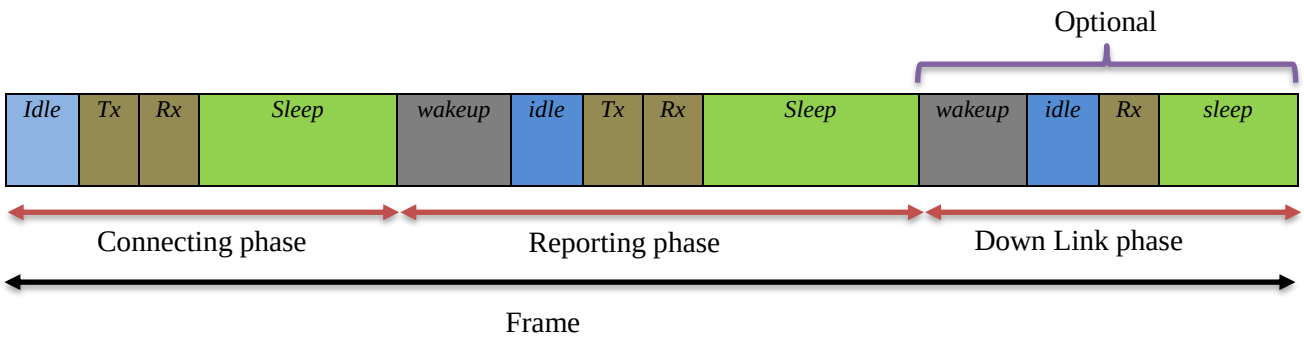

Figure 3-15: SC-MoT energy consumption pattern

3.4.1 Current Consumption Calculations

To calculate the energy consumption, we need to calculate the amount of current used by the node during each mode of the consumption pattern in Figure 3-15. The connection phase will only happen once for each node, and the downlink phase will occasionally occur. Therefore, we will highlight the reporting phase current consumption and neglect the other phases as the R_P it will happen more frequent.

The reporting phase can be divided into two parts namely, *Activemode* and *Sleepmode* as in Figure 3-16. To calculate the current consumed by a node during a full reporting phase, we do that in two steps. Firstly, we need to figure the current consumed during the *Activemode* ($C_{Activemode}$) by summing the current consumed *(I)* in every duration *(D)* of each part in the *Activemode* as in Equation (3.10). Secondly, we

calculate the current consumed during *Sleepmode* ($C_{Sleepmode}$) by calculating the time left in the frame *(FS)* and the current used in the *Sleepmode* ($I_{Sleepmode}$) as in Equation (3.11).

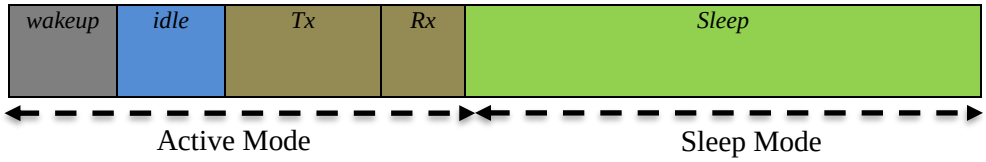

Figure 3-16: Reporting phase consumption modes

$$C_{Activemode} = (D_{wakeup} * I_{wakeup}) + (D_{idle} * I_{idle}) + (D_{Tx} * I_{Tx}) + (D_{Rx} * I_{Rx}) \quad (3.10)$$

$$C_{Sleepmode} = (FS - D_{Activemode}) * I_{Sleepmode} \quad (3.11)$$

$D_{Activemode}$**:** the duration of the active mode in the frame.

Chapter 4

SC-MoT Evaluation

In this chapter, we evaluate SC-MoT performance to assess its capabilities compared to MoT. We start by simple analytical evaluation using the equations introduced in Chapter 3. In our evaluation we used the following LoRa settings: Spreading Factor of 7, Bandwidth of 500 kHz, Coding Rate of 4/5, with explicit header and CRC enabled, and a preamble of 6 symbols. For the Time on Air (*T)*, we used LoRa calculator tool [23]. In comparing to MoT, we use the MoTSim simulator introduced in [36].

4.1 Evaluation Metrics

We represent our evaluation of different metrics. Firstly, we compare between SC-MoT and MoT in term of waiting time. The waiting time is the time a node has to wait before transmitting the next packet. The waiting time varies however with the number of nodes; therefore, we consider the minimum waiting time of each protocol at a different number of nodes.

Secondly, we compare the maximum number of nodes to be supported in different frame sizes. Thirdly, we analyze the energy consumption of SC-MoT and compare it with MoT in terms of current consumption and lifetime. By the current consumption, we calculate the consumed current during one full frame. The current consumed in one frame will change by changing the *FrameSize* as the *Sleepmode* duration will vary. Moreover, we study the lifetime of a node using 1 Ah battery across different payload sizes. In addition, we will investigate the effect of the downlink phase on SC-MoT performance. Finally, we will represent a cost analysis between SC-MoT and MoT and wrap up our work.

4.2 Evaluation

We perform multiple assessments to evaluate the performance of SC-MoT and MoT using the previous metrics. In each evaluation, we outline the test's procedures, the results and warp up with some discussion.

4.2.1 Minimum Waiting Time

We first compare the minimum waiting time required for SC-MoT and three-channels-MoT against the number of nodes in case of having one Base station (BS) for each protocol. Equation (4.1) shows the formula used to calculate minimum waiting time *(D_{min})* using the duration of the time slot *($D_{Timeslot}$)*, the number of nodes in the network *(n)*. No tolerance value is added as the $D_{timeslot}$ is already calculated with some tolerance value. We consider the same $D_{Timeslot}$, using 255-bytes as the payload, for all the nodes.

Secondly, to ensure a fair comparison between SC-MoT and three-channels-MoT, we redo the calculation using three base stations of SC-MoT and compare it with three-channels-MoT. We assume that the number of nodes will split evenly among the three BS. It is expected for the delay to be reduced significantly.

$$\boldsymbol{D_{min} = (D_{Timeslot-1} * n)} \qquad \textbf{\textit{(4.1)}}$$

- **Results**

  The plot in Figure 4-1 shows how the D_{min} is affected by the number of nodes in the network. Although MoT operates using three channels, SC-MoT still offers less D_{min} with 0.16 seconds for one node to 31.8 s for 200 nodes. On the other hands, MoT needs 5.7 s for one node and 34.29 s for 200 nodes. Thus, for networks with up to 200 nodes, SC-MoT can propose less waiting time

over MoT. However, for larger systems and due to the 3-channels feature in MoT they operate with fewer delays.

For further comparison and to achieve fairness, we used three-BS-SC-MoT to support the same number of nodes. Figure 4-2 shows the results of using three BSs against MoT. As expected the D_{min} for 200 nodes will fall to 10.6 s. Hence, it gives us the ability to relay on SC-MoT for larger networks too. Later in this chapter, a cost analysis will be demonstrated to show the cost-efficient of using 3-BS-SC-MoT against 3-channels-MoT.

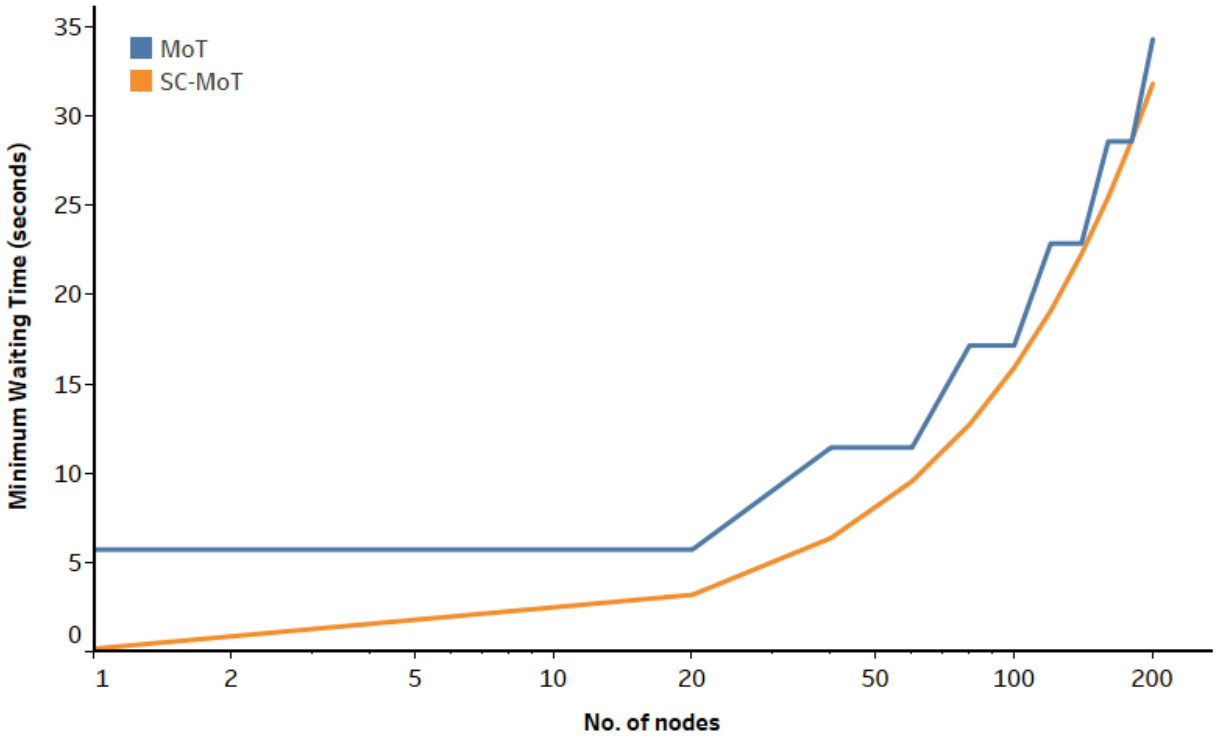

Figure 4-1: Comparison between the Minimum waiting time of SC-MoT and 3-channels MoT across a different number of nodes

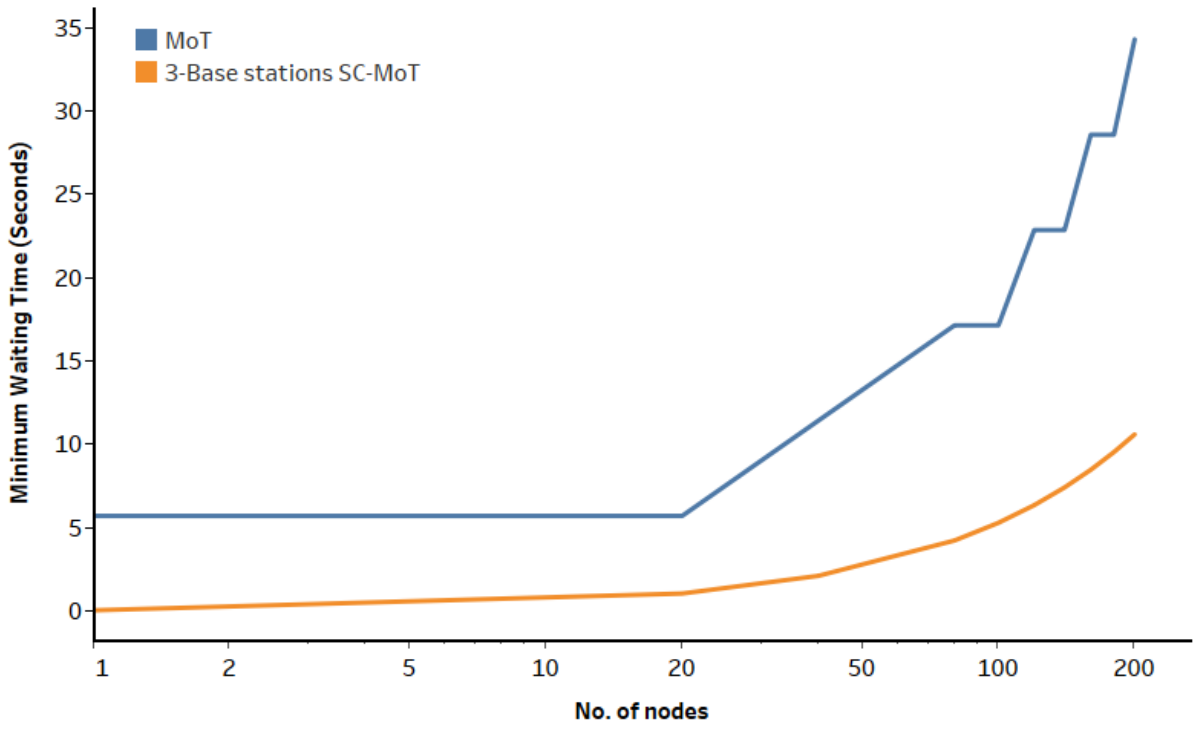

Figure 4-2: Comparison between the Minimum waiting time of 3-BS-SC-MoT and 3-channels-MoT across a different number of nodes

- **Discussion**

As shown in the results and the plots, SC-MoT showed better performance over MoT in the minimum waiting time required between the reports. Due to our design goals and the IIoT needs, SC-MoT was designed for low-density networks. Therefore, in most of the harsh IIoT applications, only 1 BS is required to support up to 200 nodes. However, in case of more nodes needed, multiple BSs will still offer lower delays than MoT.

4.2.2 Maximum No. of Nodes Supported

Here we compare SC-MoT to MoT in term of a maximum number of nodes supported *(N_{max})* across different fixed frame sizes *(FS)*. W calculated N_{max} using the $D_{Timeslot}$ assuming the same $D_{Timeslot}$ for all the connected nodes in the networks. Equation (4.2) calculates the maximum number of reports supported which cross-bound to the N_{max} for one transmission per node. Also, we repeated the test using 3-BS-SC-MoT to spot the differences.

$$N_{Max} = FLOOR\left(\left(\frac{FS}{D_{Timeslot}}\right), 1\right) \qquad \textbf{(4.2)}$$

- **Results**

The Figure 4-3 shows the change of the nodes supported by increasing the *FrameSize*. The plot shows the comparison between 1-BS-SC-MoT, 3-BS-SC-MoT and 3-channels-MoT. MoT and SC-MoT showed close results with a maximum of 507 and 467 nodes respectively for 75 seconds FrameSize. However, using 3-BS-SC-MoT for the same *FS* showed a significant rise to 1401 nodes as shown in Figure 4-3.

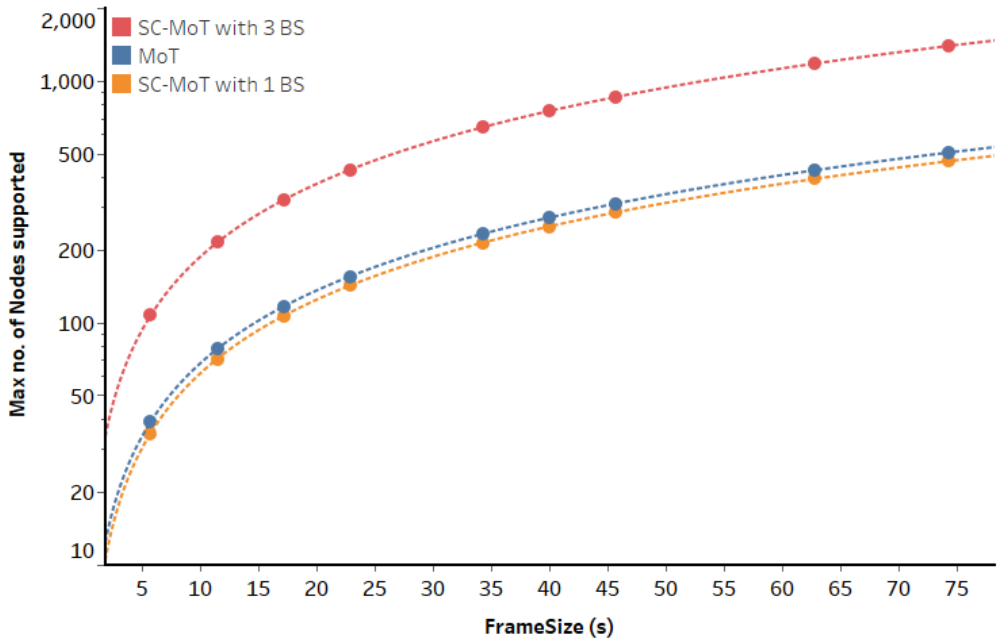

Figure 4-3: Maximum number of Nodes supported across different frame sizes

- **Discussion**

  For the most IIoT applications, only 1 BS is needed as the number of nodes required should not be extremely high. However, MoT still has slightly better result in that case. On the other hand, 3-BS-SC-MoT will offer a rise in the number of nodes supported. Hence, we can notice the significant of SC-MoT protocol in supporting a suitable number of nodes for the industrial applications.

For the rest of our evaluation, we will only consider 1-BS-SC-MoT.

4.2.3 Energy Consumption

The energy consumption is the bottleneck of many of the applications. Therefore, we study the consumption of SC-MoT and compare it with MoT results in [9]. We first calculate the current consumed

by a node *(C_{node})* during a *FrameSize (FS)* with 50-byte payload size. The FS plays an important role in the consumption; as having longer frames will lead to more C_{node} even if the node is in the *Sleepmode*. Hence, we study the change of the consumption by changing the size of the frame (*FrameSize)*. We get C_{node} in Equation (4.3) by summing $C_{Activemode}$ and $C_{Sleepmode}$ from Equations (3.7) and Equation (3.8) in **3.4.1**.

$$\boldsymbol{C_{node} = C_{Activemode} + C_{Sleepmode}} \qquad \textbf{\textit{(4.3)}}$$

Secondly, we study the lifetime in years for a node. According to [36] the number of nodes does not affect the lifetime of a single node in the network as MoT and SC-MoT offer collision free mediums. Therefore, we study the payload size *(PL)* influence on the number of years a node can serve.
We calculated the number of packets a node can successfully transmit before the battery is entirely consumed. Equation (4.4) calculates the maximum number of reports *(MaxReports)* a node can send with available battery capacity. However, Equation (4.5) gets the total lifetime in years a node can last to transmit the *MaxReports*. In our calculations, we used a 1Ah battery capacity.

$$\boldsymbol{MaxReports = FLOOR\left(\left(\frac{Capacity}{C_{node}}\right), 1\right)} \qquad \textbf{\textit{(4.4)}}$$

$$\boldsymbol{LifeTime = MaxReports\ /\ ((365 * 24 * 60 * 60)/\ FS)} \qquad \textbf{\textit{(4.5)}}$$

- **Results**

  Figure 4-4 shows the current consumption in mA between SC-MoT and MoT using a 50-byte payload while varying the *FS*. From the plot, we can spot that the current consumed by a node in MoT and SC-MoT is similar; with around 3-2mA advantages to SC-MoT. However, the reflect of the current consumption on the lifetime was clear. From Figure 5-5 we notice that SC-MoT offers a more protracted lifetime compared to MoT.

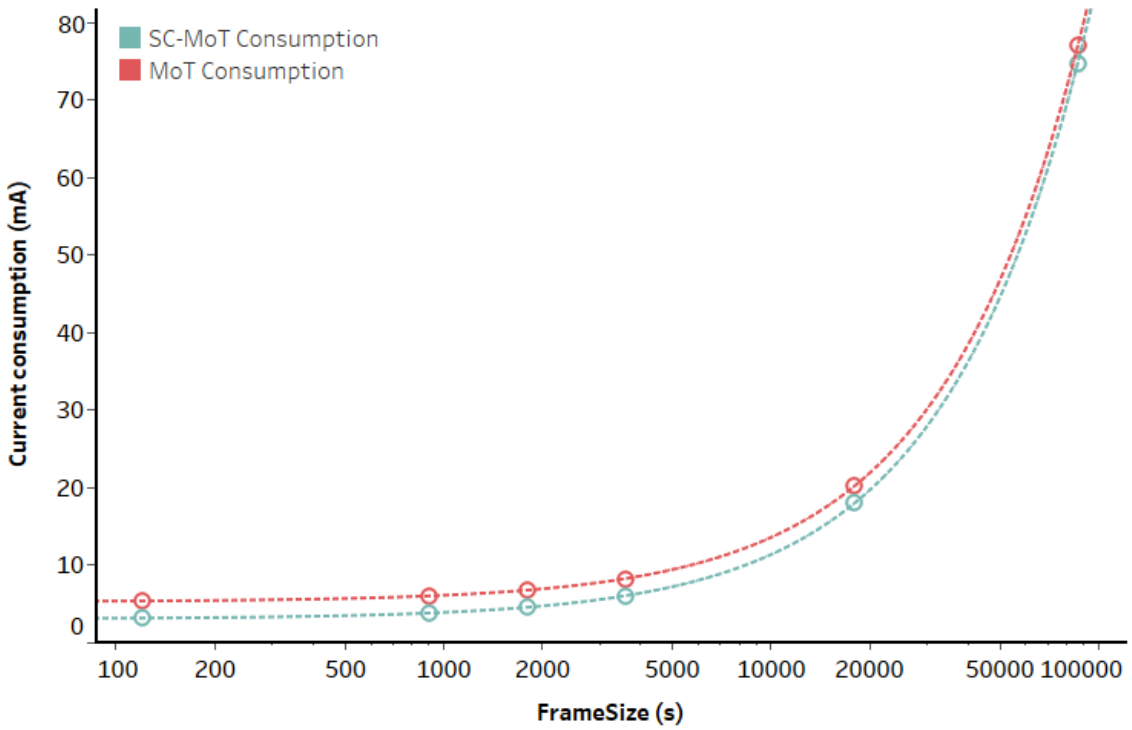

Figure 4-4: Current consumed by one node for sending 50-byte PL across different Frame sizes

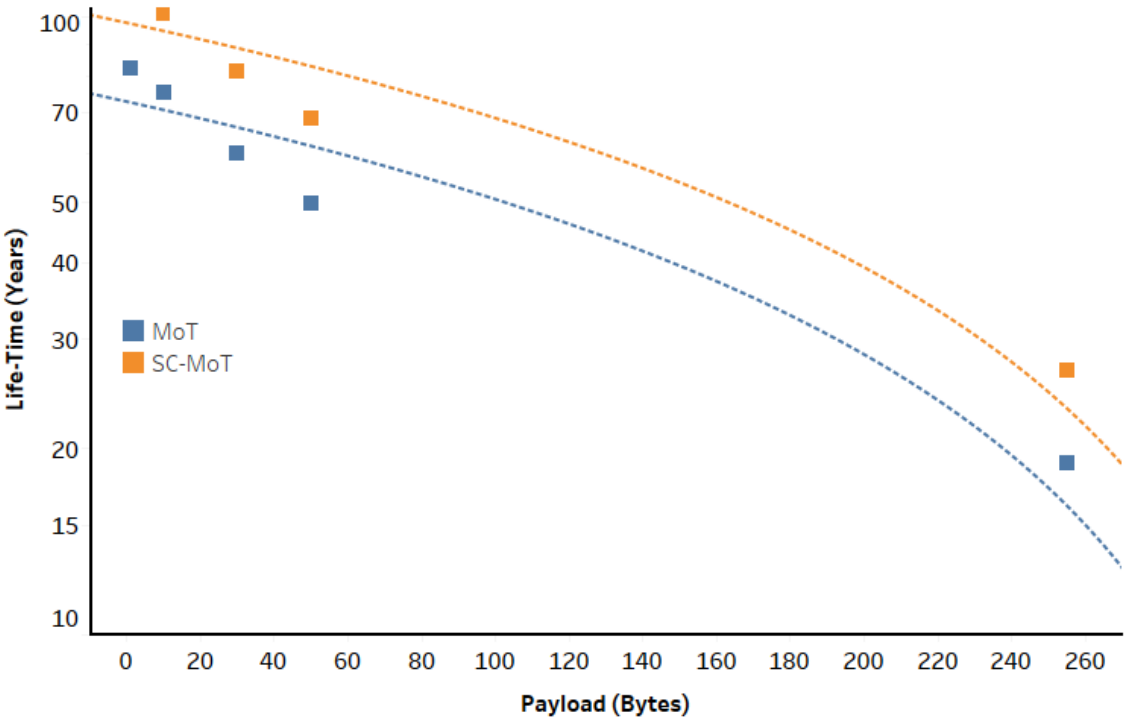

Figure 4-5: Life-Time of a single node in years, sending one packet with varying sizes of PL

- **Discussion**

From the results above, we can conclude that during fixed *FS* SC-MoT consumed slightly less current compared to MoT as shown in Figure 4-4. Such reduction in the current consumed in SC-MoT is due to the longer time SC-MoT node spent in the *Sleepmode* compared to MoT, besides, the value of the tolerance chosen.

From Figure 4-5 we conclude that overall SC-MoT will show longer lifetime as it consumes less current during each frame. Such change happens due to the different patterns the two protocols used in sending packets and receiving acknowledgments.

In short, SC-MoT shows high potential in resolving many energy issues facing the harsh IIoT application. That goes to significant of LoRa for achieving low power transmission. Besides, the efficient centralized scheduling that offers collision-free medium.

4.2.4 Downlink Effect

It is expected that implementing an extra phase in the frame might cause some delays in the transmission sequence. In this test, we try to show the effect of having a downlink phase on the delays in SC-MoT across different networks' size. Using Equation (4.6), we recalculated the minimum delay by having the DL phase. We calculate the delay with DL (D_{withDL}) for different cases depending on the probability of the presence of the DL phase in the frame (P_{DL}). That will then be added to the minimum delay (D_{min}) we calculated previously in Equation (4.1).

$$\boldsymbol{D_{withDL} = D_{min} + (D_{DL} * P_{DL})} \qquad \textbf{(4.6)}$$

In our calculation we considered three different percentage 100%, 50% and 20% that represent the probability of the DL phase presence. For instance, 50% refer to having DL phase every second frame. They were then compared with MoT and SC-MoT with no DL. The payload a node transmits is fixed to 255-bytes, and the DL packet is set to 27-bytes.

- **Results**

  From Figure 4-6 below we can see how the DL phase can affect the delays between the nodes transmissions. We can conclude that up to 100 nodes, even at 100% probability of supporting DL, SC-MoT shows a slightly higher delay against MoT with 19.48s and 17.14s, respectively. However, that rise increases by adding more nodes to the network.

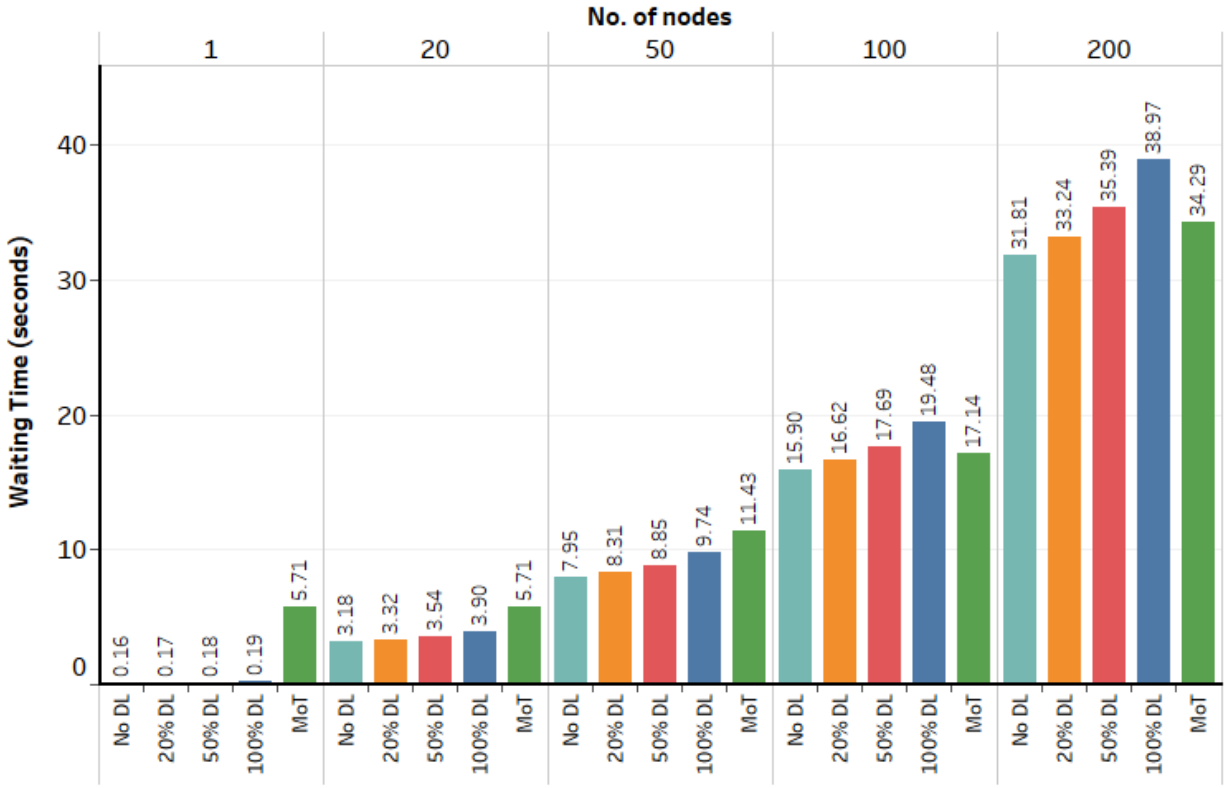

Figure 4-6: Waiting time across a different number of nodes with different probabilities of the Downlink phase appearance

- **Discussion**

  From the results, we show that supporting DL phases does not profoundly affect the waiting times of the nodes. On the other hand, the downlink phase will give the system higher capabilities to overcome critical situations.

4.2.5 Cost Analysis

Most of the industries aim for financial profits. Therefore, the cost is an effective part of many applications. In this analysis, we compare the cost of using SC-MoT against MoT.

Extra hardware or sensors added to any system can vary from one application to another. Therefore, to create fair analysis, we will only compare the LoRa transceivers used in both protocols. As in MoT, the main cost is in the base station; we analyze the ICs used in the base stations.

For our comparison, we will choose SX1301 IC for the multiple channels used by MoT's base station. On the other hand, SX1272 transceiver is used for a single channel as in SC-MoT.

According to Digi-key [38], we estimate the cost of each module using the chip prices in **Table4-1**.

Quantity	SX1301 (MoT)	SX1272 (SC-MoT)
1	67.99 US$	7.56 US$
1000	55.125 US$	4.25 US$
3000	43.4 US$	3.9 US$

Table 4-1: Comparison of the unit price between the two chips used in the BSs Transceiver in USD

- **Results and discussion**

  From the previous table, we can see the price difference between the two IC used for MoT's base station and SC-MoT. The cost for one IC that MoT uses is almost nine times the price of the SC-

MoT one. From that comparison, we demonstrate the SC-MoT outperforms MoT in the cost consumption. Hence, giving us the availability to employ multiple base stations using SC-MoT over using various channel MoT for bigger networks. Also, SC-MoT provides us with simplicity and flexibility in design; as the BS works by using the same main components and IC as the back-end nodes.

From that evaluation, we can claim that the proposed protocol (SC-MoT) gives us better performance and easier implementation than MoT for the harsh IIoT application. SC-MoT will provide an efficient system with low delays and long lifetime nodes. Besides, giving us the advantage to scalable the networks by using more BS with low cost. In addition, supporting downlink phase for command messages or OTA programming. Thus, make is suitable for many of the harsh IIoT applications.

In the next chapter, we demonstrate a practical deployment scenario in an oil-sand mine field by implementing our protocol on the Velapulsar testbed.

Chapter 5

Deployment Scenario

We demonstrate SC-MoT protocol performance in a harsh industrial field. The protocol was implemented on a hardware sensing platform namely, Velapulsar [13]. The sensing nodes were deployed inside an adapter of a digging shovel in an Oil-Sand environment. The deployment took place in Fort McMurray minefield which was one of an extended work with our Lab industrial partner SYNCRUDE Canada ltd. [12]. The sensing nodes were designed with multiple sensors to detect the status (attached/detached) of the adapters and the teeth of the shovel. However, in our work, we focus on the communication part only using SC-MoT protocol regardless the sensors readings which will be part of the payload.

We first present the Velapulsar platform illustrating its main components. In section 5.2 we run a range test under different conditions using the nodes. Section 5.3 shows the mine experiment, explaining the test scenario and objective, followed by the results and discussions.

5.1 Hardware Platform

The Figure 5-1 shows Velapulsar sensing platform that will be used in the experiments. There will be two kinds of nodes in the tests a coordinator which is programmed to work as the base station between the nodes, and a sensor node; which will be deployed to collect the data. Unlike MoT, SC-MoT have the advantage of using the same hardware platform in the coordinator and sensing nodes. Each node has a LoRa transceiver.

The microcontroller used on the board is MSP432 from Texas Instruments [39], a RFM95 module for the LoRa transceiver using the SX1272 chip. The antenna, is the flat patch 915 MHz with PCB cable that operates in the ISM band inside North America from Digi-key electronics [40]. As for the batteries, 3.6V LS14500 lithium thionyl chloride batteries by SAFT were used with a capacity of 2.6 Ah [41]. All the

experiments are to be done using one or more the Velapulsar sensing nodes. Table 5-1 shows the fixed parameters we set for LoRa transceivers inside each of the sensor nodes.

Figure 5-1: Velapulsar sensing node

Parameter	Value	Unit
Payload	*20*	*bytes*
Bandwidth	*500*	*kHz*
Coding Rate	*4/5*	-
Spreading Factor	*10*	-
Bit Rate	*980*	*bps*
Tx Power	*20*	*dBm*
Channel center Frequency	*915*	*MHz*

Table 5-1: Settings of the radio in the testing nodes

5.2 Range Test

One of the primary requirements in the industry is the ability to reach a high range to have better coverage. However, in our work, we focus on the harsh industrial environment where there is a very thick layer of metal and steel surrounding the node. Such environments suffer from the interference of the signals which greatly affect the node's range of coverage. In order to emulate the industrial atmosphere,

we did three trials. The trials took place inside (or around) the Telecommunications Research Lab (TRL) at Queen's University.

For the range tests, we used one moving node and a fixed coordinator node. We set up the frame size (FS) to be **16 seconds**. Hence, the moving node will transmit every 16 seconds to be able to record more data during the test. We used the average of five repeated tests for each trail.

1- The first experiment tests the communication under high interferences in an outdoor urban area. The experiment took place near Queen's University, following the route indicated in Figure 5-2. We measured the maximum range achieved along with the delivery status of the packets.
   We calculate the delivery ratio from the delivered packets and sent packets to find the amount of dropped packets. The total time is the time of the full experiment, and 16 seconds is the FS, we expect a packet every 16 second.

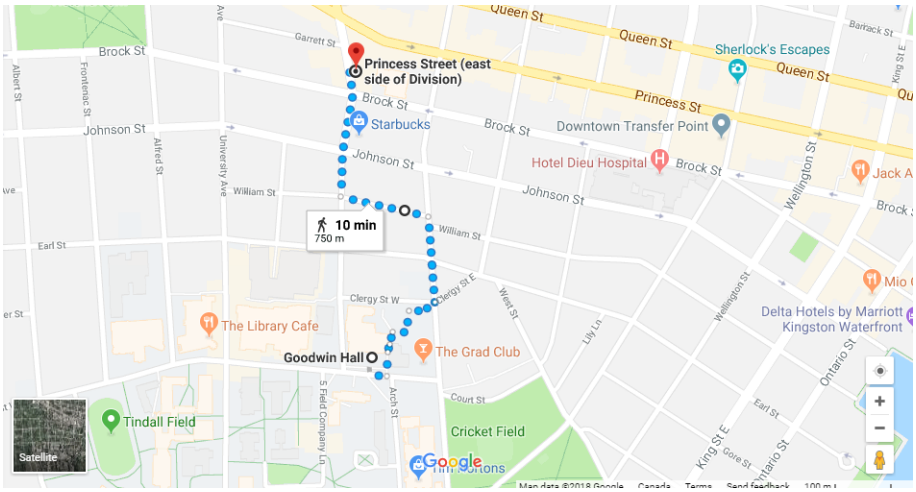

Figure 5-2: The route and the estimated distance of the experiment

2- For the second experiment, the range was tested indoors, inside the seven-storey university building. To demonstrate the system performance inside buildings with more obstacles that affects the signal. The node was moved vertically far from the coordinator and horizontally for lower floors.

3- In the third experiment, we simulate the range performance in some industrial environment where the sensor node can located inside metallic machines and enclosures. We use the enclosure designed in [19] to test the node performance inside a cavity of oil-sand digging shovels. Figure 5-3 shows the enclosure's shape used in the experiment. To double the obstacles, the experiment took place inside the building to try to achieve the worst-case scenario the node can face.

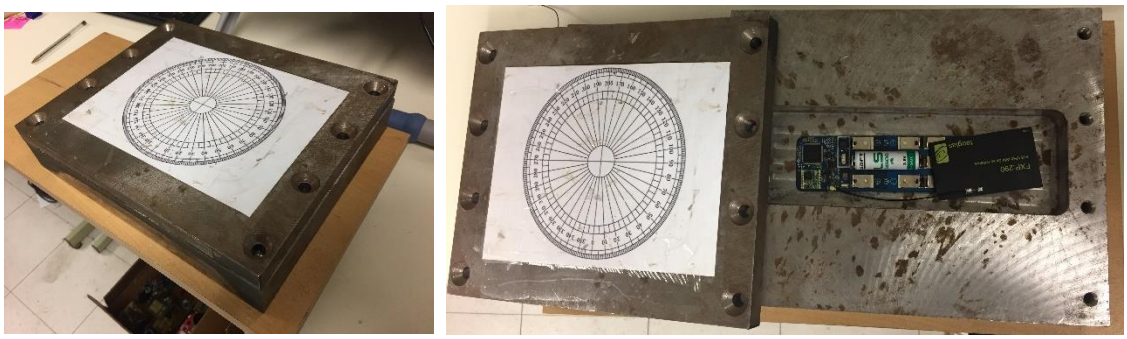

Figure 5-3: Designed enclosure for testing the nodes under critical situations

- **Results**

A. For the first test, the successfully delivered packets were 34 packets out of 38. The average delivery ratio percentage before losing the connection, was around 100%, 95% and 90% for distances of 300, 600 and 750m, respectively. The maximum average range achieved was 750m as shown in Figure 5-4.

According to that range, SC-MoT using LoRa can even be used in some Wide Area Networks (WAN) not just in the (Personal Area Networks) PAN. The reached distance and the percentage of the delivery ratio can be suitable for many applications. The Maximum range of the test can still vary; as the type of the antenna used and the link budget plays a major role in the range of coverage. Also, the number of obstacles and building can enormously affect it.

B. In the second experiment, the average maximum range achieved inside the building was calculated as 200 meters. The average delivery ratio was 95%, 82 and 74% for distances 80,

150 and 200m, respectively. Although some other technologies such as ZigBee can achieve better delivery ratio, they reach shorter ranges. The range achieved in our test is an acceptable range for the indoor applications compared to study in [42] were the ZigBee only reach up to 30m indoor.

C. For the third experiment, the average delivery ratio was approximately 95%, 78% and 69% for 15, 50 and 80m, respectively. However, the range almost cut into half compared to the indoor experiment with an average maximum range of 80m as shown in the plot in Figure 5-4.

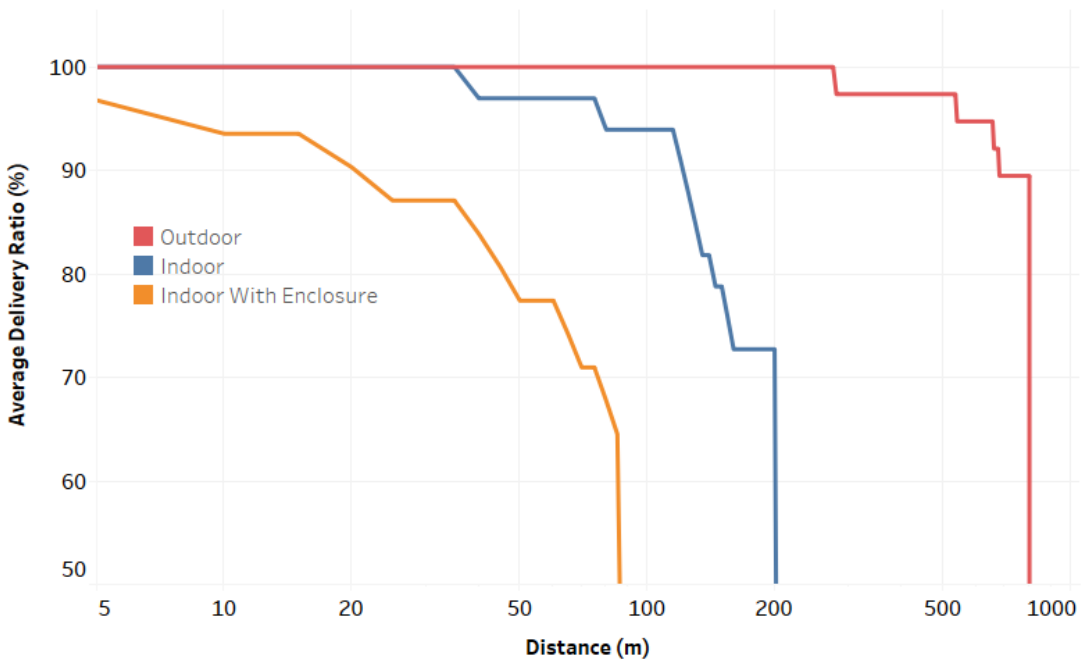

Figure 5-4: Average delivery ratio and the distances achieved across the three range experiments for the five repeated trails.

In short, the main parameter in reaching longer ranges is the physical layer, LoRa, due to its special modulation technique that enables the signal to travel for further ranges even with hitches. Acknowledging every packet is also an important factor to keep a good track of our nodes. However,

according to the three experiments, the performance is highly depending on the atmosphere and the industrial surroundings.

5.3 Field Experiment

The system of the field experiment consists of two types of wireless nodes namely, sensor nodes and a base station or sink nodes. The sensor nodes will be installed on the shovel teeth inside the cavity. The sink node will be fixed on an appropriate spot near the operator cabin.

During normal operation, the sensor nodes are continuously reporting to the sink node. The sink node is connected to a back-end server up to the front-end application to track the received reports. In case of damage or breakage, the sensor node will stop reporting which will alarm the shovel operator. If the breakage damages the sensor node, then the sink node will produce the alarm after a preset period of detection to separate the radio silence from the damaged node. It is important for the company to detect the detachment of the tooth before it reaches the crusher as it could cause huge damage and significant losses.

The nodes used in the experiments were similar to the one used in the range test, using the SC-MoT protocol as its network model. Table 5-2 illustrates the experiment duration and its parameters.

Parameter	Value
Payload	20 bytes
Frame Size	16 seconds
Transmission power	20 dBm
Receiver sensitivity	-135 dBm
Test duration	3 hours/ 5 trails

Table 5-2: Field experiment parameters

5.3.1 Test Scenario

In the test, we evaluate the protocol in an operating shovel, digging in the mine. The represented test is focusing on the delivery ratio and the fairness of the protocol. The testing steps can be illustrated as follows;

1- Before deploying the nodes inside the cavity, they have been covered with epoxy shield and left to dry to protect the node during the operation Figure 5-5. Two nodes were installed on the cavity, one on the upper and one on the lower parts, fixed with strong magnet Figure 5-6.

Figure 5-5: Velapulsar sensor node inside the epoxy

Figure 5-6: Installing the Nodes inside the adaptor

2- Moving on to an operating shovel, the technicians removed one of the shovel's bucket's adapters to replace it with the adapter carrying our sensor nodes Figure 5-7.

Figure 5-7: Removing one adaptor's bucket.

3- The adapter with the sensor nodes was then mounted on the bucket and fixed Figure 5-8.

Figure 5-8: Replacing the removed adaptor with the adaptor mounted by the nodes.

4- After installing the nodes inside the adapter and mounting the adapter on the bucket, we installed the sink node on the shovel, near to the operator cabin with a distance of 80m approximately, shown in Figure 5-9.

Figure 5-9: Installing the sink node near the operator cabin.

5- To start our test, we moved to the operator cabin to monitor the system and receive the nodes readings on the front-end application. The overall duration for one trail was around 3 hours divided as, 1 hour of installed nodes inside the bucket without operating and about 2 hours of digging operation. The experiment was repeated for five times.

5.3.2 Results and Discussions

The plot in Figure 5-10 shows the average delivery ratio pattern during the five tests; the delivery ratio was almost 100% during the standby time before the digging started. However, the ratio started to reduce when the operation started. We can see that node 1 (installed at the lower part of the cavity) achieved

better delivery that node 2 (the one installed at the upper part). There are two explanations for that; first is the hardware assembly for the nodes; as it was done manually which could affect the performance of the nodes. The other reason is the position of the antenna installed on the node. The antenna of the upper part node was upside down which might affect its performance by changing its radiation pattern especially when metal surrounds it. Node 1 had an average of the delivery ratio of 90%, on the other hand, node 2 had an average of 80% approximately.

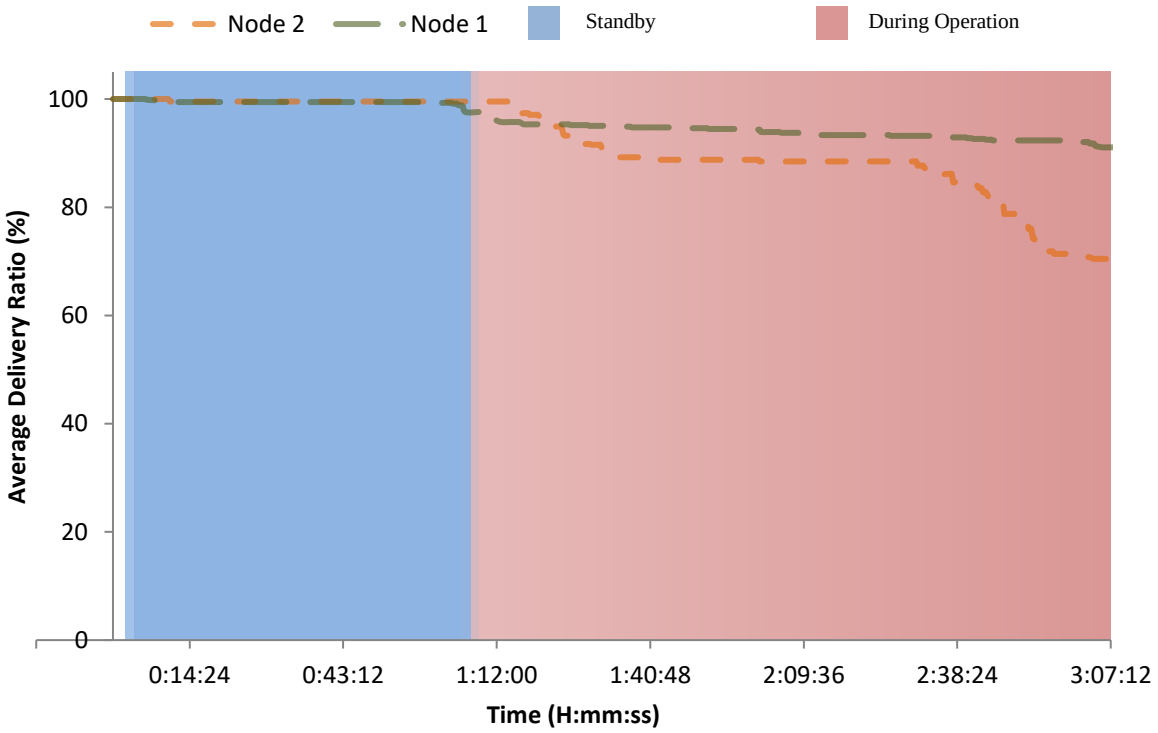

Figure 5-10: Average delivery ratio for node 1 and 2 during the five trails

Secondly, the plot in Figure 5-11 shows the average duration of connection loss (respectively dropped packets) for both nodes during the five experiments. Node1 had an average maximum of 96 seconds of connection loss, i.e. 96 seconds of not receiving any packets, which reflects 6 undelivered packets respectively (6 * 16 seconds = 96 seconds).

For node 2 the average maximum duration of continuous connection loss was 112 seconds; 7 undelivered packets. However, as observed in the plot node 2 exposed higher drop rates which lead to an overall longer time of connection loss.

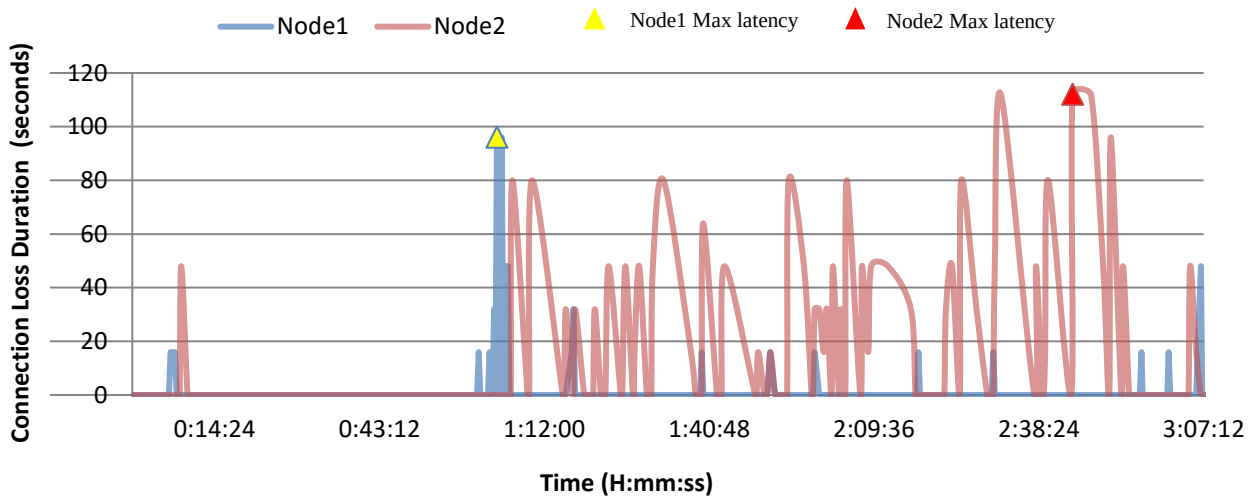

Figure 5-11: The average duration of connection loss for node 1 and 2 during the five trails

- **Discussion**

1- We can see the effectiveness of LoRa in such system, as the transceiver enabled the wireless connectivity within the steel structure of the adapter. Also, the centralized scheduling assured the time-slot availability for each node and the fairness between them.

2- The acknowledging after every packet in SC-MoT helped to keep efficient tracking of the nodes inside the cavity.

3- Packets drop were mainly due to the failure of the transmitted signal to reach the receiver sink node. Failure happened due to the massive movement of the bucket while digging in the mine.

Besides, the metal surrounding the node from all the direction leads to high interferences and losses in the signal.

4- According to the results above, that protocol in that environment showed acceptable results especially by node 1. However, those results could improve significantly in a better environment or fields with less metal surrounding.

5- The permitted connection loss duration varies depending on the application. For instance, according to the previous results, applications that can accept the loss of the connection for 90 seconds straight would be suitable to use that protocol.

6- Fewer obstacles can provide a reduction in the drop packets, besides, broader connection coverage. Hence, better environment using SC-MoT can work efficiently; see Figure 5-10 during the standby period.

Chapter 6

Conclusions

The deployment of the IoT technology is taking place in different industrial fields known as Industrial IoT (IIoT). However, there are many harsh and critical conditions that different industries face nowadays. Issues such as metallic obstacles, Long transmission range requirements and emergency situations are some of many problems in the harsh industries. Therefore, deploying IIoT comes with a lot of requirements and restrictions.

In this dissertation, we introduced a new MAC protocol SC-MoT that is an IIoT adaptation of the MAC on Time (MoT) protocol [36]. MoT is multiple channel MAC protocol on top of the LoRa PHY layer, which achieves low latency and long lifetime. LoRa PHY layer is one of the new top technologies that offers low transmission power and long range of communication with a low bit rate.

MoT showed a great improvement in the waiting time, throughput, and the energy consumption compared to LoRaWAN (a MAC protocol designed for LoRa PHY layer). However, issues such as lack of downlink support and the lateness in acknowledging the arrival packets make it unsuitable for many critical tracking applications. In addition, MoT's base station cost and complexity added few complications in using it in industries with limited resources.

SC-MoT is a single channel protocol, designed with multiple features added to MoT. SC-MoT is a centralized scheduling MAC protocol that works with a centralized base station which coordinates all the nodes in the network. Unlike MoT, SC-MoT is a single channel protocol that divides every frame into two phases namely, connecting phase and reporting phase, plus an optional downlink phase. In SC-MoT a node connects to the network during the connecting phase, and then sends reporting data during the reporting phase in a previously scheduled time-slot assuring a collision-free medium. To achieve energy efficiency, the nodes get active only during the time-slot otherwise they switch to sleep mode. SC-MoT base station directly acknowledges every received packet making this a superior protocol for tracking

schemes. The downlink support proposes over the air programming and might be used for sending commands to the nodes anytime.

Compared to MoT using 3-channels, SC-MoT showed improvements in the minimum waiting time required between the transmissions in networks with up to 200 nodes. However, that improvement was even tripled by comparing 3-channel MoT against 3-base stations SC-MoT. As for the maximum number of nodes supported, MoT still showed slightly higher capabilities in supporting more nodes due to the multiple channels feature. However, comparing 3-base stations SC-MoT with MoT showed higher abilities for SC-MoT to support more nodes.

Compared to MoT, SC-MoT consumes less current to transmit the same payload. The different sleep durations and communication pattern between SC-MoT and MoT lead to different results for the lifetime. Overall SC-MoT showed longer lifetime as a node spend more time in a sleep mode leading for higher energy efficiency.

The evaluation of the downlink effect on the waiting time showed positive results. Having a downlink phase in every frame will still perform better than MoT in networks with up to 100 nodes.

The cost efficiency demonstrates one of the leading advantages of SC-MoT over MoT. MoT base station is multiple channels. Therefore, the cost of the LoRa chip used in MoT's base station is nine times more expensive than the chip used in SC-MoT. The base station in SC-MoT uses the same chip as the network's nodes use, enabling the use of the same hardware for both the nodes and the BS. Hence, adding flexibility and simplicity to the implementation. Therefore, using a 3-base station SC-MoT is more efficient than using 3-channels-MoT from both the performance, and cost perspective.

SC-MoT was deployed on the Velapulsar sensing platform to evaluate the performance in real field experiments. The range was tested in three different conditions. The outdoor range around urban areas reached 750m with least delivery ratio of 90%. Conversely, the indoor test reached a distance of 200m with an average least delivery ratio of 74%. To emulate the harsh condition in an industrial field; the node was located in a metal enclosure for the third range test. The maximum range exceeded our expectation

reaching 80m with an average delivery ratio of 69% at its worse. However, the latter test was made indoors to add more obstacles.

Finally, two nodes were mounted on an adaptor in a minefield shovel to test the tracking performance. During the standby time, before the shovel operates, with a distance of 80m, the delivery ratio was almost 100% with no dropped packets. However, during the operating time, the delivery ratio average for the two nodes dropped to an average of 85%. That drop happened due to the harsh movement and vibration during the digging operation causing interferences and connection loss.

SC-MoT still has its share of limitations. The peer-to-peer communication between the nodes is not supported, as nodes can only communicate with the BS. Therefore, SC-MoT is not efficient for applications that require communication between the deployed nodes. In addition, according to the results SC-MoT with one BS can only support a limited number of nodes which could make it unsuitable for few applications.

In short, SC-MoT protocol showed acceptable results and suitable performance that gives it a high potential in the IIoT applications. However, in many applications the harsh atmospheres require more than having efficient protocol. The hardware design, the sensor node protection and the right placement play another significant role.

As a future direction we plan to reevaluate SC-MoT with more nodes in lab experiments scenarios to calculate the waiting time, number of nodes supported and the energy consumption more efficiently. Furthermore, we plan to modify SC-MoT to support peer-to-peer communication to make it suitable for more industrial applications.

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