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MASTER'S THESIS

CoAP and MQTT Measurements over LoRaWAN

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ABSTRACT

Internet of Things (IoT) enables the system of interrelated computing devices such as sensors and actuators. Thus, IoT faces few challenges to execute predefined functionalities during device-to-device communication. Low latency, high bandwidth, privacy, security, reliability, resource and energy efficiency are key challenges in the IoT paradigm. The fundamental requirement includes uninterrupted secure and reliable services. The challenges become even more controversial for low powered IoT devices during information over the long-distance (measured in kilometer) especially when the bandwidth is subject to free of cost. Different network layer supports are required for present Internet of Things (IoT) solutions – from applications at a higher level to media-based support at a lower level. The interoperability of the fragmented IoT solutions are being enabled by various emerging integration platforms. However, Long-Range Wireless Area Network (LoRaWAN) is used to exchange small data packet in such long distance. On the other hand, IoT required suitable communication protocols for power critical IoT devices. Many studies show the possibility of using Message Queue Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP) as two major enabling IoT communication protocols to act as middleware to obtain low power consumption, sporadic transmission, and robustness to interference. The main basis of the thesis work is to measure and analysis the performance of the MQTT protocol over LoRaWAN. To implement the analytical approach, MQTT and CoAP protocols are used as a transport vehicle or interoperability middleware on a full TCP/IP-stack to connect end devices, and data transmit over the LoRaWAN.

This thesis performed the analytical performance for different Spreading Factors (SF) or Data Rates (DR) along with different payload sizes (the message length) over LoRaWAN by using MQTT and CoAP protocols. In LoRaWAN, the Receive_Delay1 and Receive_Delay2, the minimum time duration needed to establish an MQTT connection is one second for Receive_Delay1, while the maximum is two seconds for Receive_Delay2. The analysis shows for uplink and downlink time and proposes various important facts for future aspects.

Keywords: LoRaWAN, MQTT, CoAP, IoT, Spreading Factor, Uplink, Downlink, CONNECT, DISCONNECT, and PUBLISH.

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FOREWORD

This Under the Faculty of ITEE of the University of Oulu, this thesis has been prepared to successful completion for the International Master's Degree Programme. This work is done at the Centre for Wireless Communications research unit at The University of Oulu as a partial completeness of master's degree requirement in ECE and the accomplishment of the thesis work is set to measure CoAP and MQTT over the LoRaWAN . After completing all of my tasks of this paper, I will be able to increase my practical knowledge and the theoretical knowledge. I become familiar with CoAP, MQTT, and LoRaWAN. From my point of view, the whole works are only possible to complete with the guidance of esteemed researchers who are working in this diverse research unit. In my words of gratitude to both supervisor and technical supervisor on my thesis are greatly helpful. The guidance of you at each stage made the timely accomplishment of the work possible. Konstantin Mikhaylov (Assistant Professor), thanks a lot for being a part of my journey, your suggestions were the appropriate directions for me. My supervisor on the thesis, Dr. Jussi Haapola (Adjunct Professor), thanks for your encouragement and supervision. Without your proper directions, the completion of the work was not possible anymore. I would you like to say thanks to my friends particularly, Md Johirul Islam, Md Sanaullah, Md. Ziaul Hoque and Famida Afroz Lopa for their company and fun during the course of my master's journey I will be grateful that whoever reads my thesis work many years from now, I can appreciate the hardship and struggle you are going through. It is my own suggestion, do not lose your hopes as there is always a bright light at the end of a tunnel. Whereas I also faced great problems and tried to struggle to find out my exact results, and then I was able to solve my questions and problems at the end. By exploring my own situations, I am going to say that just stay focused and keep doing the good work. Nothing is impossible in the thesis tasks. You have to find out your problems and solve them, as I did my works.

Oulu, Finland, July 24, 2020

Md Kamrul Hasan

LIST OF ABBREVIATIONS AND SYMBOLS

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation Mobile Networks
ABP	Authentication By Personalisation
ACK	Acknowledgement
AES	Advanced Encryption Standard
ALOHA	Additive Links On-line Hawaii Area
AMQP	Advanced Message Queuing Protocol
API	Application Interface
AS	Application Server
ASCII	American Standard Code for Information Interchange
AWS	Amazon Web Services
BLE	Bluetooth Low Energy
BW	Bandwidth
CoAP	Constrained Application Protocol
CON	Confirmable
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CT	Connection Timeout
dB	Decibel
DR	Data Rate
E2E	Exchange to Exchange
ED	End Device
ETSI	European Telecommunications Standards Institute
FOpt	Fields of Proficiency Testing
GW	Gateway
HTTP	Hyper Text Transfer Protocol
IBM	International Business Machines Corporation
IETF	Internet Engineering Task Force
IH	Implicit Header
IoT	Internet of Things
IPv4	Internet Protocol Version 4
ISM	Institute for Supply Management
ITEE	Information Technology and Electrical Engineering
KAT	Keep Alive Time
Kbps	Kilobits Per Second
KHz	Kilohertz
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LoWPAN	Low-power Wireless Personal Area Networks
LPWA	Low Power Wide Area

LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LWM2M	Lightweight Machine to Machine
LWT	Last Will and Testament
M2M	Machine-to-Machine
MAC	Media Access Control
MB	Megabytes
MHz	Megahertz
MQTT	Message Queuing Telemetry Transport
NAT	Network Address Translation
NB-IoT	Narrowband Internet of Things
NON	Non-Confirmable
NS	Network Server
OASIS	Organization for the Advancement of Structured Information Standards
PHDR	Physical Header
PHY	Physical Layer
PL	Payload
QoS	Quality of service
RAM	Random Access Memory
RFC	Request For Comments
RL	Remaining Length
RST	Reset
SCADA	Supervisory Control And Data Acquisition
SCTP	Stream Control Transmission Protocol
SF	Spreading Factor
SMQTT	Secure Message Queue Telemetry Transport
TCP/IP	Transmission Control Protocol/Internet Protocol
TKL	Token Length
TLS	Transport Layer Security
ToA	Time On Air
UDP	User Datagram Protocol
URI	Uniform Resource Identifier
Wi-Fi	Wireless Fidelity

$n_{preamble}$	*Programmed Preamble Length*
$n_{payload}$	*Number of Payload Symbol*
RS	*Symbol Rate*
RX	*Receiver*
$T_{preamble}$	*Preamble Length*
T_{packet}	*Packet Duration*
T_{sym}	*Symbol Period*
+/-	*Plus, or Minus*

1 INTRODUCTION

With the enhancement in the number of end-users and the increasing demand for machine to machine communication use cases, it emerges that the existing communication system will soon need a major evolution. Communication technology, especially wireless technology has become an important part of our life, offering flexible choices based on connectivity and DRs. To achieve long connectivity, over six miles, and optimal date rate, long-range (LoRa) devices and long-range wide area network (LoRaWAN) protocol has some distinguished features [1].

The LoRaWAN is a specification for wireless communication. Compared to other technologies such as wireless fidelity (Wi-Fi), narrowband-Internet of things (NB-IoT) and long-term evolution for machine type communications (LTE-M), LoRaWAN is more suitable for this thesis work for a number of reasons. LoRaWAN is a newly wireless technology intended for low-power wide area network (LPWAN) with low cost. It has low power consumption and an optimized protocol designed for scalable wireless networks with millions of devices. MQTT is an inconsequential publish and subscribe system where one can publish and receive messages as a client. LoRaWAN supports long-range communication for MQTT [28]. The MQTT protocol has much more messages but in this thesis, three messages which are analysed with different spreading factors of LoRaWAN. Furthermore, CoAP is also one of the most recent usage layer protocols established by the Internet Engineering Task Force (IETF) for smart devices to link up the internet. Thus, lightweight protocol MQTT and CoAP are expected to be deemed and used as a replacement of HTTP [3]. Lightweight protocol means any protocol that has a leaner and lesser payload when being transmitted and used over a network connection. It is simpler, easier and faster to manage than other communication protocols used on a local and wide area network. These protocols are also needed for low power consumption.

1.1 Demand of LoRaWAN

One of the essential disruptions is brought by LoRaWAN technology to the IoT market. It is the potential technology to spread any type of business standard from implementing privately. It is also owned networks to subscribe connectivity to a LoRaWAN operator. LoRaWAN technology is efficient for indoor or rural. Whereas LoRa technology is variable for indoor or rural. Moreover, the cooperative nature of LoRaWAN has been promoting the emergence of global open developer communities [1]. To support the remarkable demand for bandwidth, new technology has entered the IoT field and it is called the LoRaWAN. It saturates the technology gap of Cellular and wireless fidelity / Bluetooth low energy (BLE) based networks that require either high power or high bandwidth or have a limited range or inability to enter deep indoor environments. LoRaWAN technology is efficient for indoor or rural use cases in smart homes, smart cities, buildings, smart metering, smart agriculture and logistics and smart supply chain. Figure 1 shows the LoRaWAN position compared to the other technologies.

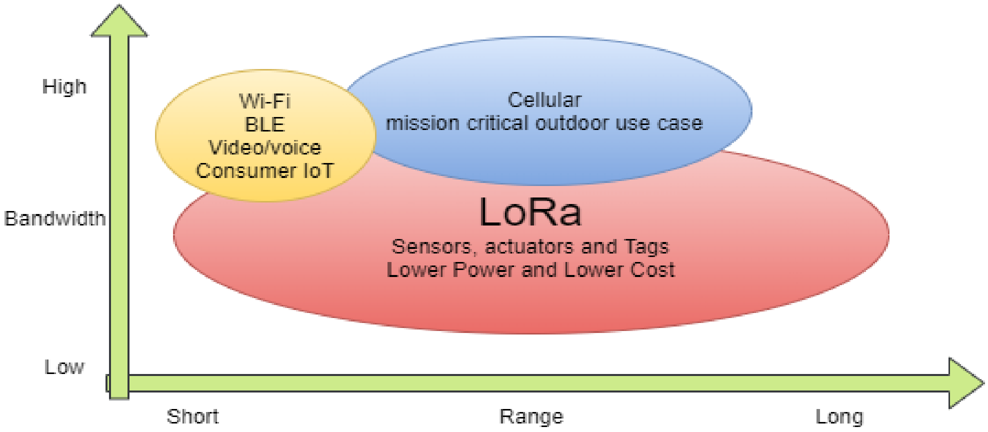

High
Bandwidth
Low
Short
Range
Long
Wi-Fi
BLE
Video/voice
Consumer IoT
Cellular
mission critical outdoor use case
LoRa
Sensors, actuators and Tags
Lower Power and Lower Cost

Figure 1. Different technologies [4].

1.2 The objective of thesis

For completing the objective of this thesis, it must measure the MQTT and CoAP protocols over the LoRaWAN in an analytical way. In this thesis work, the new LoRaWAN technology will be used as the base technology. It is known that LoRaWAN is low-power wide-area network (LPWAN) [5]. In this work, different messages of MQTT needs to be analysed using the various spreading factors (SFs) and payloads. Depending on the spreading factors, the maximum payload size in Europe per message is from 55 to 250 bytes. In this case, three messages, which are key for the MQTT uplink operation, i.e., connect, disconnect and publish will be used for analysis. The LoRa uses the 868 MHz frequency band and this frequency is license-exempt for usage. LoRa is also used for long-distance information transfer. The LoRa modulation will enable to obtain up to 20 km transmission with low power. All these criteria will be analytically discussed to obtain the concrete result. The LoRaWAN has three classes (A, B and C) which will help to get the result in this thesis work. The result will be described as a table at different time duration for required messages.

1.3 The approach of thesis

In this section, the methodology of the work will be discussed. In this work, two lightweights widely used protocols such as MQTT and CoAP have been selected. Prior to that many protocol characteristics such as protocol key features, security, ability and comparison with other protocols have been studied. In the comparison view, it is found out that MQTT and CoAP are the most suitable protocols. Hence, three messages of MQTT protocols over the LoRaWAN technology has been used for further analysis because MQTT is used for many to many communications. An analytical study has been conducted to get time duration for different messages of the protocols regarding the connecting, disconnecting and publishing. A complete description about DR, SF and bandwidth (BW) can be found in my thesis work. Depending on the DR, SF and BW total time duration of the protocol messages varies.

2 RELATED WORK

This chapter describes the related work respective to the thesis objective. There are several protocols which are working similarly with MQTT and CoAP protocols. To understand the significance of the selected protocols, a deep study has been conducted about similar technology in this work. Furthermore, LoRaWAN has also similar technologies which are described.

2.1 Related Protocol

In this related protocol work, It has selected the advanced message queuing protocol (AMQP) and Secure Message Queue Telemetry Transport (SMQTT) [6]. MQTT is a lightweight protocol because all its messages have a small data footprint. Every message consists of a fixed header two bytes, an optional variable header, a message payload. This limitation is to 256 megabytes (MB) of information and quality of service (QoS) level.

2.1.1 Advanced message queuing protocol

Advanced message queuing protocol (AMQP) is called an open standard subscribe/publish type protocol. AMQP is a new Organization for the Advancement of Structured Information Standards (OASIS) standard and it runs over the transmission control protocol (TCP) [6]. Although AMQP has secured some ground inside the information communication technology, it is still quite limited on the internet of things (IoT) industry. Furthermore, the AMQP specification defines such elements as message orientating, queuing, routing (including point-to-point and publish-and-subscribe), dependability and security. It is probably the only protocol feasible for an end-to-end application with such models as weighty industrial machinery or Supervisory control and data acquisition (SCADA) systems, wherever the devices and the network are significantly efficient as a rule [7]. However, the most crucial different standards are that the broker is separated between exchange and queues, as shown in Figure 2.

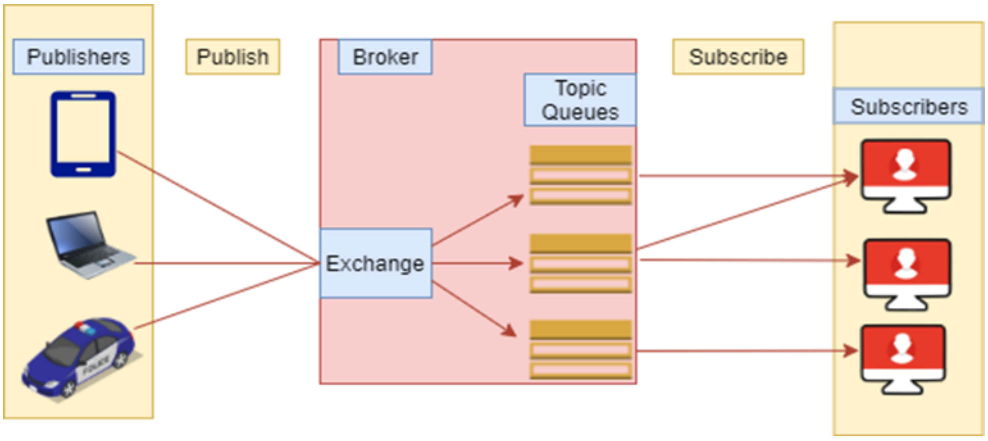


Figure 2. AMQP architecture [8].

The AMQP is an application layer protocol. The publish/subscribe (pub/sub) is meant to decouple the client that sends as a publisher from the client or clients that receive as subscribers.

The client is any device of AMQP. The connection of a publisher and a subscriber is controlled by the broker. The broker is a server which receives all messages.

2.1.2 *Secure Message Queue Telemetry Transport*

SMQTT stands for Secure Message Queue Telemetry Transport which uses encryption based lightweight attribute-based encryption. The most important advantage of utilizing such encryption is the broadcast encryption feature, in which one message is being encrypted and delivered to several other nodes, which is very common in IoT applications [25]. SMQTT is intended only to enrich the MQTT security features. Figure 3 [6] shows SMQTT protocol [7]. Figure 3 is described in detail in below how sender publisher and receiver subscriber are communicating through the broker.

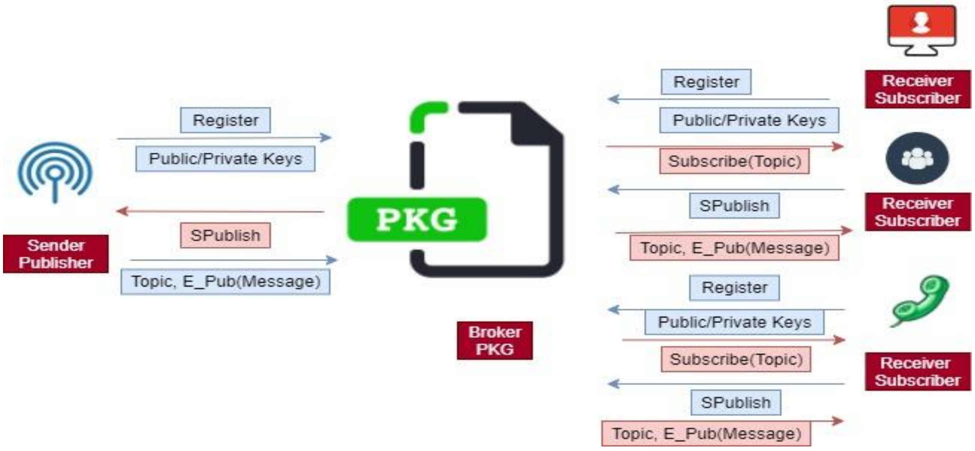


Figure 3.Secure MQTT protocol.

The broker receives all messages from different clients. After receiving the messages, it is used to route the proper destination clients. There are some public and private messages that are received. The broker can receive all clients' messages.

2.2 Related Technology

In this chapter, it has made a comparison of different related technologies. Among them, here is selected LoRaWAN technology for the thesis work and Table 1 shows in addition Narrowband Internet of Things (NB-IoT) and Long Term Evolution (LTE-M). It just highlighted the parameters of all the technologies. These are low power consumption technologies.

Table 1. Different low power technologies [9]

Technology Parameters	LoRaWAN	NB-IoT	LTE-M
Bandwidth	125 kHz	180 kHz	1.4 MHz
Battery Life	15+ years	10+ years	10 years
Coverage	165 dB	164 dB	156 dB
Throughput	50 kbps	60 kbps	360 kbps
Security	AES 128 bit	3GPP (128 to 256 bit)	3GPP (128 to 256 bit)

NB-IoT is also a low power wide area (LPWA) technology used to support a wide range of new IoT services and devices. It also significantly enhances the power consumption of user devices, spectrum efficiency and system capacity, especially in deep coverage. LTE-M is also a type of low power wide area network radio technology standard. The power consumption of LoRaWAN is less compared to NB-IoT and LTE-M. While it consumes less power, LoRaWAN also gives a longer battery life compared to LTE-M and NB-IoT (15+ years compared to 10+ years). According to the above table, the battery life is better than LTE-M and NB-IoT. The coverage of LoRaWAN is better than other technologies [9].

3 LORAWAN

The LoRaWAN has some specifications making it a long-range, low power wide area networking protocol [2]. It is designed for connecting battery operated ‘things’ to the internet in national, regional or global networks. The key targets are IoT requirements for such as bi-directional communication, end-to-end security, mobility and localization services [1]. Low power wide area (LPWA) networking technology is the long-range communication, which empowers new forms of services. There are several existing solutions for LPWA among which LoRaWAN is unquestionably the most highly adopted one [10]. It ensures pervasive connectivity in outdoor IoT applications while maintaining network configurations and management simple [10]. LoRaWAN architecture defines an end to end data transfer solution, as illustrated in Figure 4 below. The end devices(EDs) are basically several types of sensors that communicate with LoRaWAN gateways (GWs) using the LoRa physical layer protocol mainly on sub-GHz license-exempt bands such as 915MHz in USA, 868MHz in EU, and 470MHz in China [38].

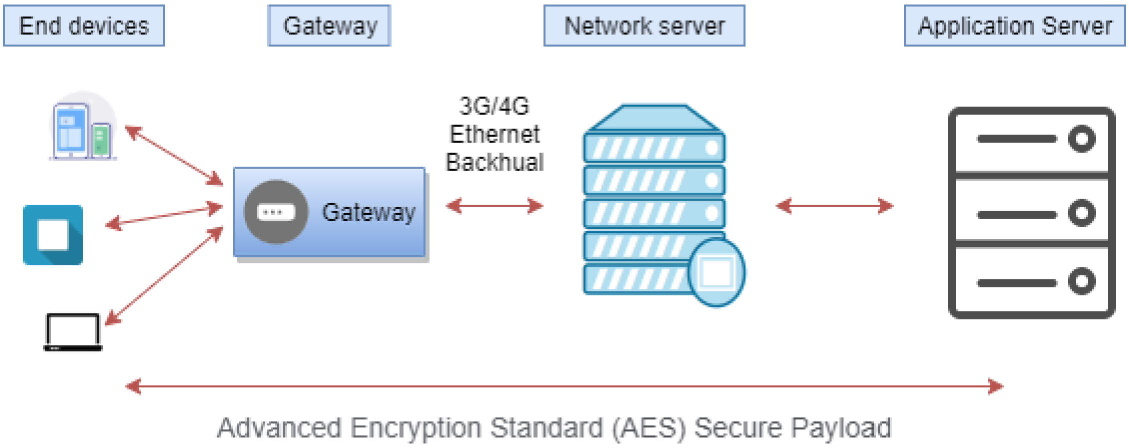


Figure 4. LoRaWAN solution architecture [15].

As stated by Figure 4, several components are defined in a LoRaWAN as end device(ED), gateways(GWs), network server and applications. The GWs perform with the EDs by using LoRa and LoRaWAN technologies. GWs send out the LoRaWAN frames from the EDs to a network server which is used as a back-haul interface with higher bandwidth typically Ethernet, 3G/4G [6]. The definition of LoRaWAN GW being as "one distributed antenna, common to all networks" strengthens GW like a physical layer device with an inactive role in the overall network [15]. LoRaWAN requires network server (NS) and an application server (AS) and this idea can initially cause a little uncertainty. The AS hosts the applications. Such a NS is needed because GWs can be considered "dumb" – sending all sensor data with a small amount or no intelligence applied to what is sent [38].

3.1 LoRaWAN Technology

Theoretically, the LoRaWAN specification contains three major components, such as physical layer (PHY), the link layer and the network architecture [34]. The physical and link layers specify the communication between a GW and an ED. LoRaWAN network is deployed in a star topology where the GW relay data message between the ED and the network server. The communication in the middle of an end node and GW are bidirectional. LoRaWAN consists in different layers, a media access control (MAC) layer is one of them and it has been added to regulate and extend the LoRa physical communication layer on top of the LoRaWAN specification but below the application layer [16]. This MAC layer is known as the LoRaWAN specification. The specification is public sourced, and it is adopted by the LoRa Alliance. The LoRaWAN protocol also consists of a key wireless network features such as adaptive data rate optimization, quality of service, exchange to exchange (E2E) encryption, security and other advanced communication applications [12]. It is a new technology, remote and spread-spectrum modulation method. It permits sending data at very low data rates for very long ranges. The LoRaWAN modulation and low data-rate (down to few bytes per second) leads to very low receiver sensitivity (down to -136 dBm). The maximum output power of +14 dBm means very large link budgets; up to 165 dB [9]. It means more than 22 km (13.6 miles) in line of sight (LOS) links and up to 2 km in non-line of sight (NLOS) links in the urban environment (going through buildings) [13].

3.2 LoRaWAN Specification

The LoRaWAN network protocol has a special specification which is enhanced for battery powered EDs. LoRaWAN networks typically maintain GWs relay messages between EDs and a central NS. The NS can route the packets from each device of the network to the related AS. So the LoRaWAN has three classes which are described below in Figure 5 [14]. The figure shows different classes and other layers.

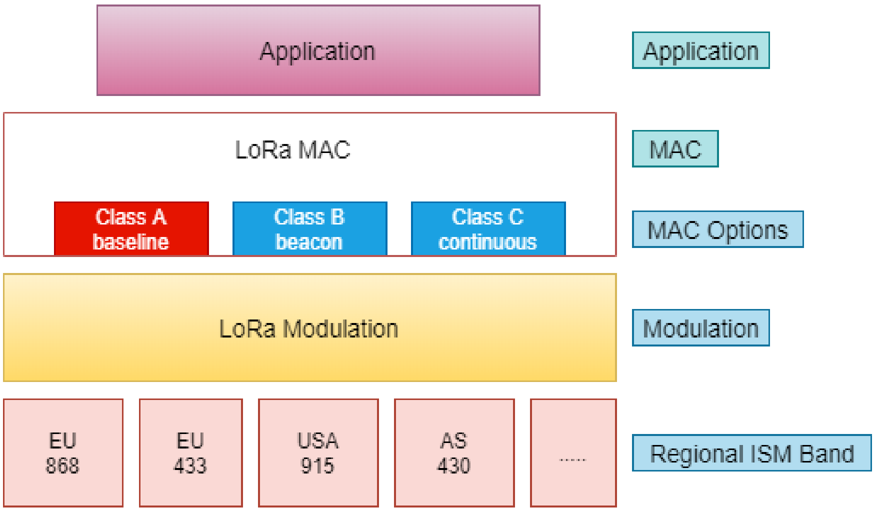


Figure 5. LoRaWAN classes [32].

In the MAC options of Class A, when the uplink packet of end nodes, two downlinks are scheduled to open to deliver a downlink packet. The Class A is the most energy-efficient, however, it has the highest latency [32]. Class A has the basic class implementation in every LoRa ED, and it aims applications with low-rate downlink data. It is also confirmed low energy consumption and corresponds to low powered devices

3.2.1 Class A

In Class-A, EDs of allowing for bi-directional communications. Each EDs uplink transmission is supported by two short downlinks receive windows. The slot of the transmission scheduled by the ED, which is based on its own communication, requires a small variation which is based on an arbitrary time basis (ALOHA-type of the protocol). In class A, there are physical message formats which distinguish between uplink and downlink messages.

Uplink Messages: These messages are sent by EDs to the NS and relayed by one or many gateways. The uplink messages make use of the LoRa radio packet explicit mode in which the LoRa physical header (PHDR) combined with a header cyclic redundancy check (CRC) (PHDR_CRC) are contained. Here integrity of the payload is covered by a CRC. The physical header Cyclic Redundancy Check (PHDR_CRC), PHDR and payload CRC fields are put in by the radio transceiver [14]. Table 2 shows the uplink PHY structure.

Table 2. Uplink PHY structure [14]

Preamble	PHDR	PHDR_CRC	PHYPayload	CRC

3.2.1.1 Receive Windows

Each uplink transmission of the ED opens two shorts receives windows. The receive windows are RX1 and RX2. The receive window start times are specified using the end of the transmission as a reference, as shown in Figure 6.

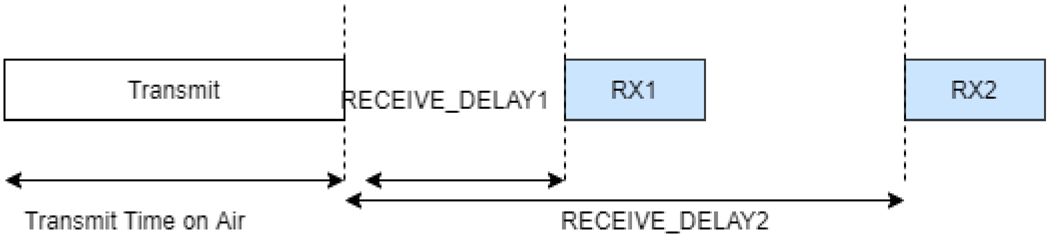


Figure 6. End devices receive slot timing [14].

3.2.2 Class B

In Class B, EDs also allow for more receive slots compared to the Class A random receive windows. Here Class B devices must open extra receive windows at scheduled times. At the scheduled time, the ED opens it receives window and it also receives a time-synchronized beacon from the GW. EDs of Class B support for a network. All the GWs synchronously broadcast a beacon, delivering a timing reference to the EDs. According to this timing reference, the EDs which can periodically open receive windows, hereafter is called “ping slots”. The “ping slots” can be used by the network infrastructure to initiate a downlink communication. A network is begun downlink using one of these ping slots is named a “ping”. The GW selected to initiate this downlink communication is chosen by the NS based on the signal quality signs of the last uplink of the ED. Figure 7 of beacon reception slot and ping slots illustrate below [14].

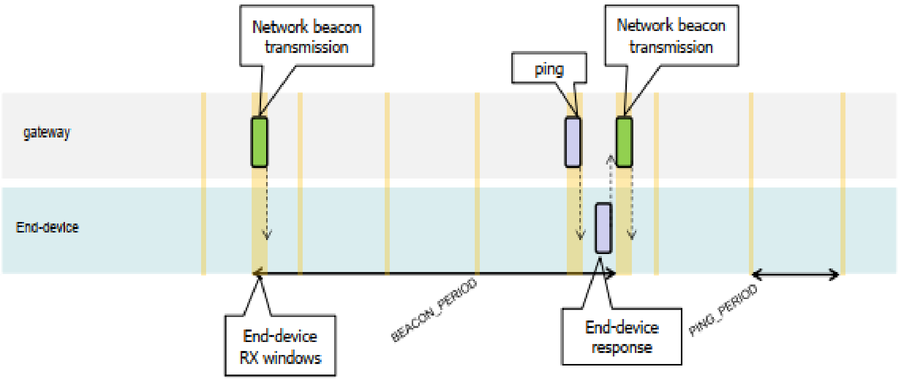


Figure 7. Beacon reception slot and ping slots [14].

3.2.3 Class C

EDs of Class C almost always open received windows. The receive windows are closed during the transmission. In Class C, ED will use more power to work than Class A or Class B, but it recommends the lowest latency for server and ED communication. Class C devices implement the similar two receive windows as Class A devices. However, they do not close the RX2 window until they need to send again. So, they may well receive a downlink in the RX2 window at nearly any time, with downlinks sent for the purpose of ACK transmission or MAC command. In Figure 8 shows in Class C ED reception slot timing.

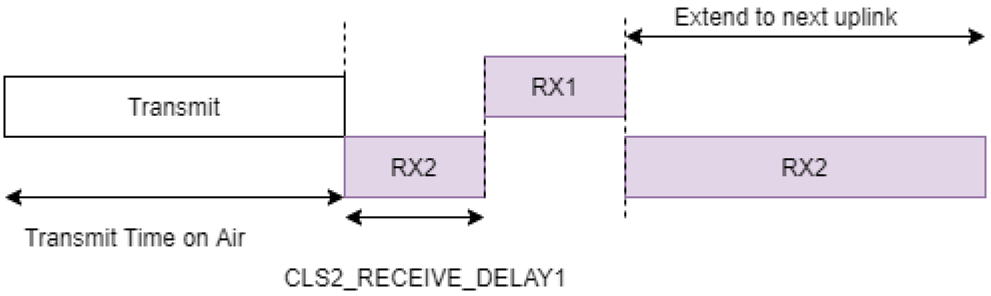


Figure 8. Class C end device reception slot timing [14].

3.3 LoRaWAN Parameters

With the intention for support, the identification of LoRaWAN channel plans referenced by other specification documents and the table below offer a quick reference of common name and channel plans listed for every formal plan name. Table 3 shows the regional parameter common names.

Table 3. Regional Parameter Common Names [41]

Channel Plan	Common Name
EU863-870	EU868
US902-928	US915
CN779-787	CN779
EU433	EU433
AU915-928	AU915
CN470-510	CN470
AS923	AS923
KR920-923	KR920
IN865-867	IN865
RU864-870	RU864

According to the European channel plan, this thesis works to select EU 868.

3.3.1 Band channel frequencies for the EU

This section operates to the EU region where the ISM radio spectrum use is defined by the European Telecommunications Standards Institute (ETSI). For accessing the physical medium, the ETSI regulations require some restrictions such as the maximum and the maximum time can transmit per hour. There is no limitation for a dwell time of the EU863-870 PHY layer. The TxParamSetupReq MAC command is not implemented in EU863-870 devices. The following encoding is applied for Data Rate (DR) and ED EIRP (TXPower) in the EU863-870 band. EU863-870 TX Data rate Table 4 is shown in below.

Table 4. EU863-870 TX Data rate table [41]

Data rate (DR)	Configuration	Indicative physical bit rate [bit/s]
0	LoRa: SF12 / 125 kHz	250
1	LoRa: SF11 / 125 kHz	440
2	LoRa: SF10 / 125 kHz	980
3	LoRa: SF9 / 125 kHz	1760
4	LoRa: SF8 / 125 kHz	3125
5	LoRa: SF7 / 125 kHz	5470
6	LoRa: SF7 / 250 kHz	11000

So LoRa has multiple bandwidths such as 125 kHz, 250 kHz and 500 kHz. The 500 kHz is not used in the EU. In EU863-870, the maximum MAC Payload size length (M bytes) is provided by the following Table 5. It is obtained from the limitation of the PHY layer dependent on the efficient modulation rate used to consider a possible repeater encapsulation layer. In maximum application, payload size in the absence of the non-compulsory fields of proficiency testing (FOpt) control field (N) is also provided for information only. The value of N may be tinier if the FOpt field is not clear: Table 5 illustrates the EU863-870 maximum payload size (repeater compatible).

Table 5. EU863-870 maximum payload size (bytes) [41]

Data rate (DR)	M(bytes)	N(bytes)
0	59	51
1	59	51
2	59	51
3	123	115
4	230	222
5	230	222
6	230	222

If the end device will never function with a repeater then the maximum application payload length in the non-appearance of the optional FOpt control field will be.

Table 6 shows EU863-870 maximum payload size (not repeater compatible).

Table 6. EU863-870 maximum payload size(bytes) [41]

Data rate (DR)	M(bytes)	N(bytes)
0	59	51
1	59	51
2	59	51
3	123	115
4	250	242
5	250	242
6	250	242

4 CONSTRAINED APPLICATION PROTOCOL

The Constrained Application Protocol (CoAP) is a particular web transfer protocol for use with constrained networks and constrained nodes in the IoT. It is used for machine-to-machine (M2M) applications, for example, smart energy and building automation. It is improved as an Internet Standards in the document, RFC 7252 [21]. It has been projected to last for years still there are some difficult issues. According to the architectural view, such as hypertext transfer protocol (HTTP), CoAP is a document transfer protocol. The HTTP together with CoAP is designed for the demands of constrained devices, whereas CoAP packets are far smaller compared with the HTTP TCP protocols. CoAP is constructed to inter-manage with HTTP [17].

4.1 CoAP Structure Model

The CoAP communicating model and HTTP are a client/server model and are comparably the same. CoAP consists of a two-layers structure which is illustrated below. The first message layer is called the bottom layer and it is designed to an agreement with the user datagram protocol (UDP) and asynchronous switching. In addition, the communication method is concerned with the request/response layer and dealt with the request/response message [18]. With the standardizing of CoAP, for instance, Lightweight Machine to Machine (LWM2M) currently uses CoAP over UDP as a transport. Support for CoAP over TCP allows it to report the issues above for specific placements and to protect investments in current CoAP applications and deployments [20]. Figure 9 shows the model of the CoAP structure.

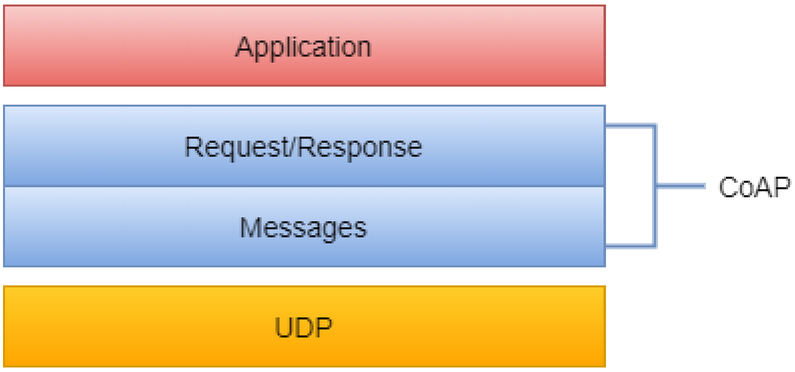


Figure 9. Basic structure model of CoAP [21].

4.1.1 Messaging model

In this layer, there are four types of messages which are called CON (confirmable), NON (non-confirmable), ACK (Acknowledgement) and RST (Reset). These four types of messages are described reliable message and unreliable message transport [18].

The reliable message transport system: It must retransmit while waiting for getting ACK with a similar message ID, applying default timeout and reducing calculating time exponentially while CON is being transmitted. If any receiver is unable to process the message, it will be responded with the replacement of ACK with RST. The reliable message transport is illustrated in Figure 10 below [3].

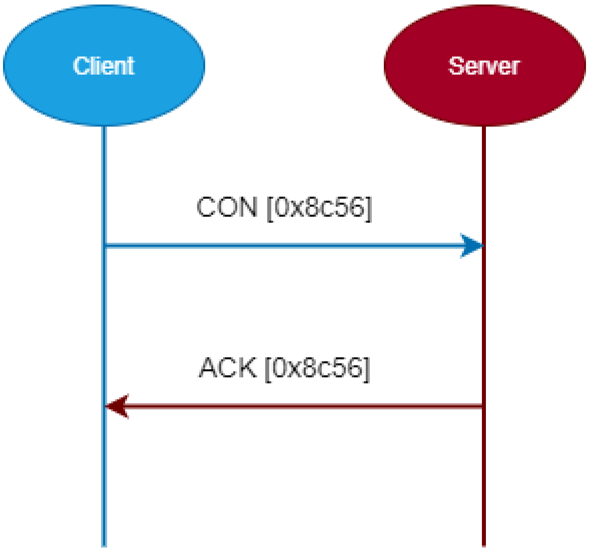


Figure 10. The reliable message transport [3].

The unreliable message transport-system: Here, the message transporting system is NON-type. If it contains a message ID, it will not need to be ACKed to oversee in case of re-transmission. The unreliable message transport-system is illustrated in Figure 11.

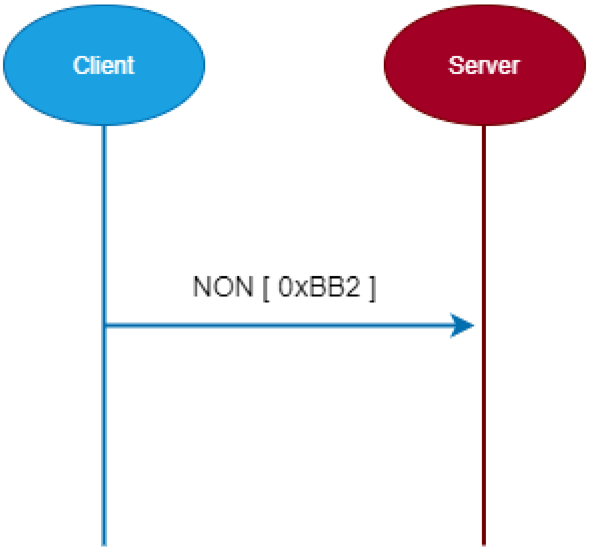
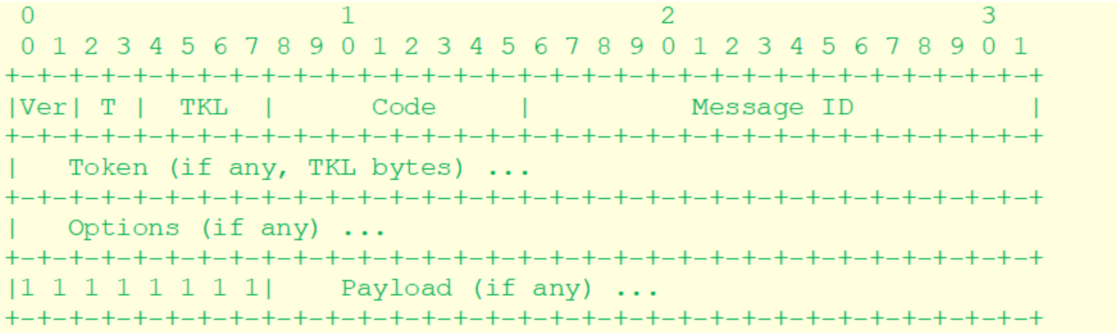


Figure 11. The unreliable message transport [3].

4.2 CoAP Message Format

In CoAP message format, there are four bytes of binary fixed-length header. The format of CoAP messages is encoded in an easy binary way. Every message is included with a specific Message-ID. Message-ID is applied to distinguish duplicate packets and ensure reliability. Dependability is provided by publishing a message as CON. A Confirmable message is re-communicated, applying a default timeout and exponential back-off between re-transmissions until the receiver transmits an ACK message with a similar Message-ID. Figure 12 demonstrates the CoAP message format. The description is also discussed below.



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Ver| T |  TKL  |      Code     |          Message ID           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Token (if any, TKL bytes) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Options (if any) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 1 1 1 1 1|    Payload (if any) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 12. CoAP message format [19].

Version (Ver): Here the 2-bit integer is unsigned, and the CoAP version number is indicated. It should be set to 1 (01 binary). Additional values are held in reserve for future versions. Messages with undetermined version numbers must be mutely unheeded.

Type (T): 2-bit unsigned integer. In this section, the messages are indicated by the type of Confirmable (0), Non-confirmable (1), Acknowledgement (2), or Reset (3)

Token Length (TKL): This section is discussed about 4-bit unsigned integer. It is showing the length of the variable-length Token field (0-8 bytes). The reservation lengths are 9-15 which should not be sent and need to be dealt with as a message format error.

Code: In this 8-bit unsigned integer, the code is divided into a 5-bit detail (least significant bits) and 3-bit class (most significant bits). It is known as "c.dd" wherever "dd" are two digits from 00 to 31 for the 5-bit subfield, and "c" is a digit from 0 to 7 for the 3-bit subfield. The class can signify a request (0), a success response (2), a client error response (4), or a server error response (5). (All other class values are reserved).

Message-ID: In the network byte order, the message-ID is unsigned 16-bit integer. Message duplication applies for detection and it is also matched with the messages of the type ACK/Reset to the messages of type Confirmable/Non-confirmable.

Token: The Token is applied to match up a response with a request. The token value maintains a sequence which ranges from 0 to 8 bytes. Every Single request carries a client-created token that the server must echo (without modification) in any subsequent response.

Options: A list with one or more options might be included with both requests and responses. For instance, the URI in an application is transferred in several options and metadata that would be kept in an HTTP header in HTTP is provided as options as well [20].

5 MESSAGE QUEUE TELEMETRY TRANSPORT

MQTT(Message Queue Telemetry Transport) is a publish/subscribe, extremely simple and a lightweight messaging protocol that allows embedded devices with restricted resources (CPU, RAM, battery, etc.) to operate asynchronous communication on a constrained network [22]. It is called the machine to machine(M2M) connectivity protocol [43]. The MQTT protocol is designed for low-bandwidth, constrained devices, and untrustworthy networks [44]. The model principles are to reduce network bandwidth and device resource requirements whereas, also attempting to make sure reliability and some degree of assurance of delivery. These principles are also used to create the protocol standard of the outgoing "machine-to-machine" or "Internet of Things" world for connected devices. These devices are used for mobile applications and in this case, the bandwidth and battery power are at a premium. As its name indicates, it is well-matched for the telemetry data transport as sensors data. It can also be used for other purposes, as example- the Facebook Messenger application for smartphones uses the MQTT protocol for the messages exchanged in the middle of the clients [23]. The architecture of MQTT is depicted in Figure 13.

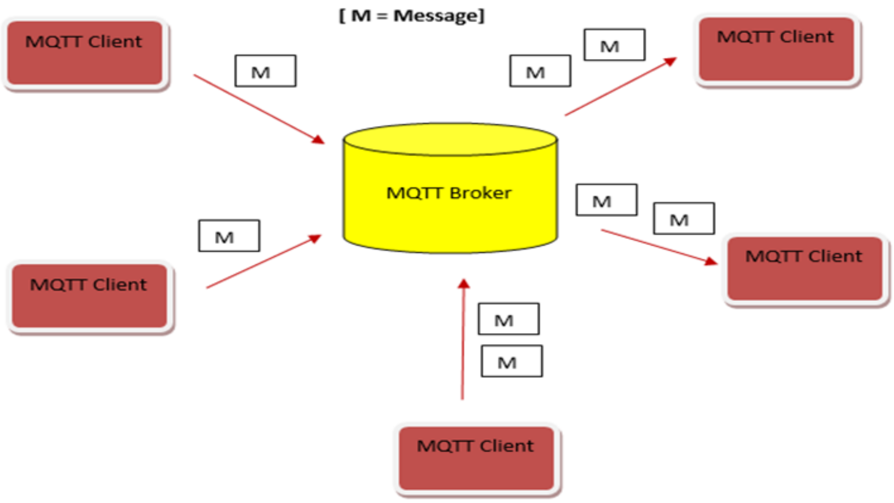


Figure 13. Simple MQTT architecture of broker and client [22].

Generally, the MQTT protocol with a network contains lots of clients (up to ten thousand devices) and a server known as "broker". Every single client connects to the broker running its own unique identifier (client ID). Client connections are managed with the role of the broker to transfer messages between them. Moreover, the responsibility is kept by the broker for handling any message persistence and the broker can transmit them to the clients that were for the moment disconnected but returned online; this feature is named "retain message". A client ought to send a keep-alive message regularly to the broker to maintain the connection alive when it is in idle state (not pulling or pushing messages) for a long time. If not, the broker dismisses the connection after a timeout. Fundamentally, a connection timeout is computed by the following equation.

$$CT = 1.5 \square KAT, \qquad (1)$$

where CT is the connection timeout and KAT is the keep-alive time. Along with the equation, the connection time is proportionate to the keep-alive time. Every part of the architecture is based on TCP/IP, which is a suite of communication protocols used to interconnect network devices. Every message switched between clients is packaged inside a TCP packet. Figure 14 shows the TCP packets where messages are wrapped inside. TCP/IP is called a set of standardized rules that permit computers to communicate on a network such as an internet [22].

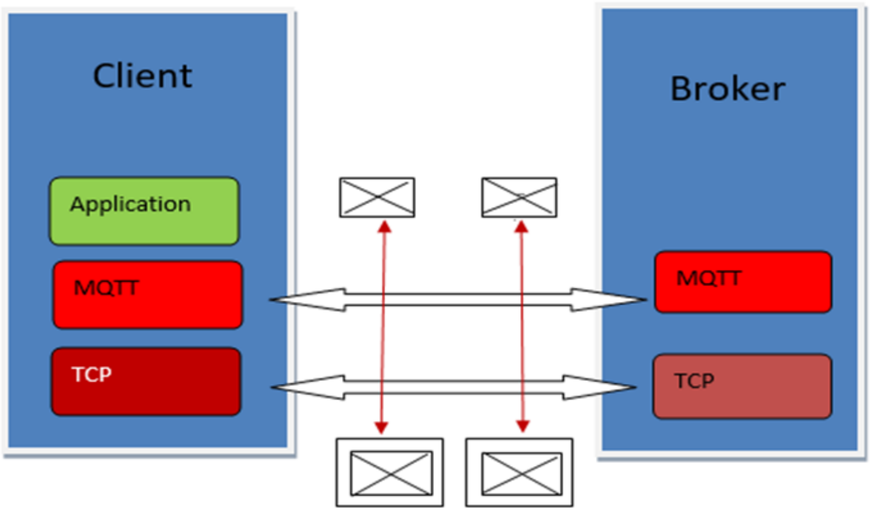


Figure 14. MQTT is based on TCP/IP [22].

5.1 MQTT Protocol

MQTT is one of the good commonly employed protocols in IoT projects. This protocol is a lightweight protocol and it is also simple to implement in software and better-speed data transmission. The MQTT protocol is very fast in delivering messages by using a messenger/WhatsApp message [23]. The communication model is asynchronous with messages. It decouples the data producer (publisher) and data consumer (subscriber) through topics. MQTT is a simple protocol, aimed at low complexity, low footprint implementations and low power [24]. It is going on connection-oriented transport (namely TCP). While MQTT has been intended to be easy to implement, it yet comprises relatively complex protocol logic for controlling connections, subscriptions and the numerous qualities of service levels related to message delivery. According to the QoS, the MQTT protocol delivers application messages on three levels. The delivery protocol is aimed exclusively to delivery of an application message from senders to receivers [25]. The MQTT protocol also has some core elements, such as clients, servers (=brokers), sessions, subscriptions and topics [24]. The core model of MQTT is shown in Figure 15.

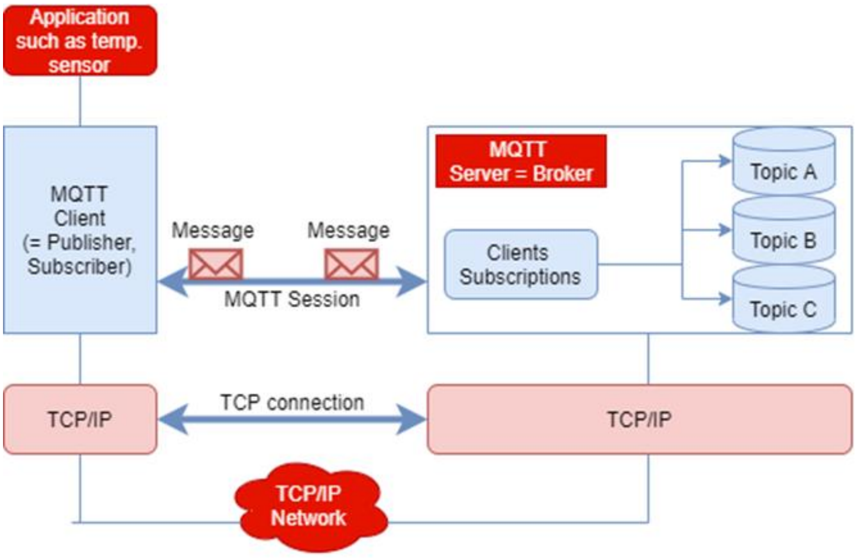


Figure 15. MQTT core model [24].

Therefore, clients are subscribed towards topics on the way to publish or receive messages. Hence subscriber and publisher are exclusive roles of a client shown in Figure 16.

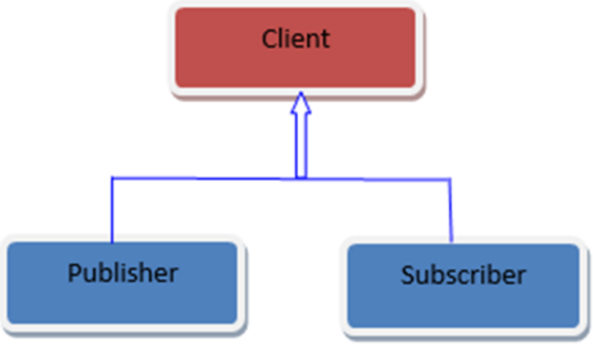


Figure 16. Client combination of publisher and subscriber [24].

Server topics are employed to receive subscriptions from clients and receive messages from clients and these are also forwarded depending on client's subscriptions to create an interest in the clients. Theoretically, topics are known as message queues. Topics improve the publish/subscribe form for clients. Rationally, topics let clients exchange information with defined semantics. Figure 17 shows the exchanging information.

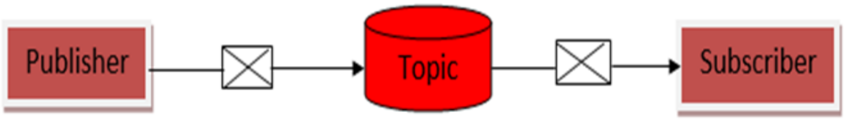


Figure 17. Topic with message queues [24].

5.2 MQTT Message format

A mandatory fixed-length header which is two bytes, an optional message-specific variable length header and message payload is contained with the MQTT messages. The optional fields generally make protocol processing difficult. Though MQTT is optimized for bandwidth-constrained and unreliable networks (typically wireless networks), Whereas the optional fields are employed to decrease data transmissions quickly. MQTT is a protocol based on a binary and the control elements are binary bytes and not text strings [26]. MQTT uses a command and command acknowledgement format. The description of MQTT usage is explained in Figure 18 for network byte and bit ordering [24]. Table 7 also shows the fixed header fields in a short description.

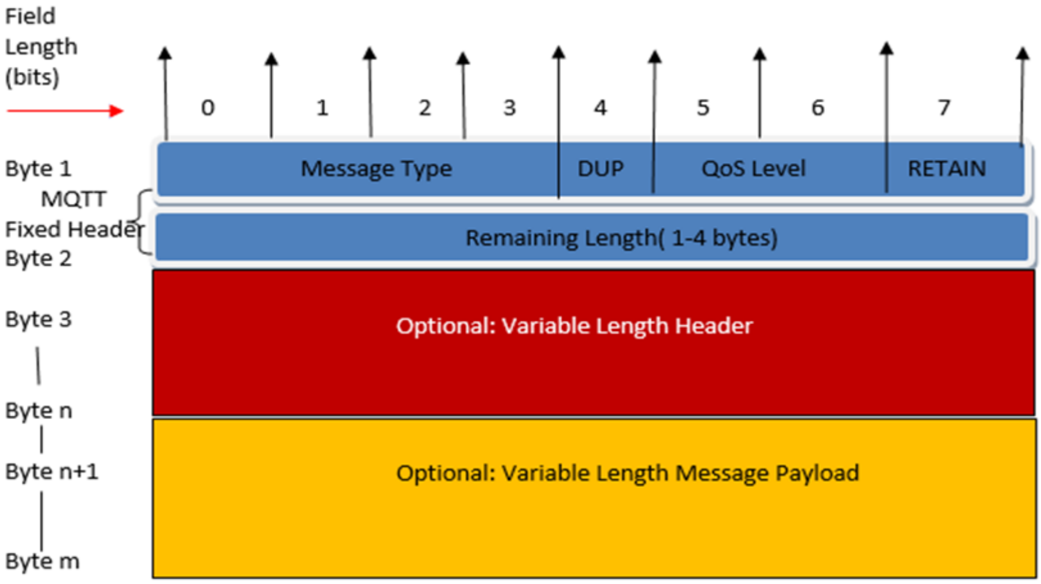


Figure 18. MQTT uses network byte and bit ordering [24].

Table 7. The overview of fixed header fields is described by the table [26]

Message fixed header field	Description / Values
Message Type	0: Reserved 8: SUBSCRIBE 1: CONNECT 9: SUBACK 2: CONNACK 10: UNSUBSCRIBE 3: PUBLISH 11: UNSUBACK 4: PUBACK 12: PINGREQ 5: PUBREC 13: PINGRESP 6: PUBREL 14: DISCONNECT 7: PUBCOMP 15: Reserved
DUP	Matching message flag. Shows to the receiver that this the message may have meanwhile acceptance. 1: Server (broker) or client re-delivers a PUB, REL, PUBLISH, SUBSCRIBE or UNSUBSCRIBE message (duplicate message)
QoS Level	Signifies the level of distribution assurance of a PUBLISH message. 0: At-most-once delivery, no guarantees, «Fire and Forget». 1: At-least-once delivery, acknowledged delivery. 2: Exactly once delivery. Further details see MQTT QoS.
RETAIN	1: According to the order, the server to hold the last received PUBLISH message and transmit it as a first message to the new subscriptions. Further details see RETAIN (keep the ending message).
Remaining Length	Turns the number of remaining bytes in the message, i.e. the length of the payload(optional) and the variable length header (optional). More details also see Remaining length (RL)

5.2.1 RETAIN message format

When RETAIN=1, the server is instructed in a PUBLISH message to keeping the message. After subscribing to the topic, a new client with the server sends the retained message. Typical application scenarios: changes are published for the clients in the data, so subscribers obtain the very last known good value. Example: Subscribers take the last known temperature value from the temperature data topic. RETAIN=1 signifies to subscriber B and in this situation, the message may possibly be published sometime in the past. Figure 19 shows the RETAIN message format.

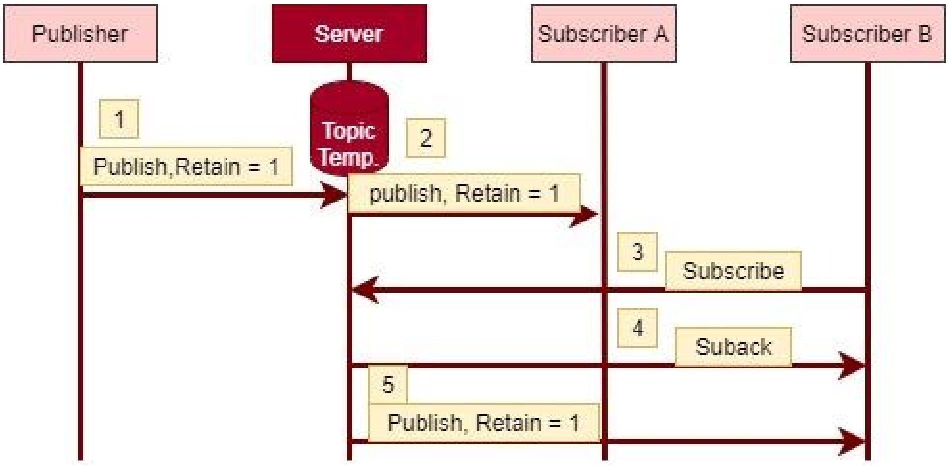


Figure 19. Retain = 1, publisher [24].

In the Retained message, MQTT broker stores that message and sends it to any new subscriber. The messages which will be used in implementation are CONNECT, DISCONNECT and PUBLISH. These messages are needed to enable delivery of the uplink data for which the LoRaWAN is optimized. The connection of MQTT always exist between a client and a broker. Clients are never able to connect to each other directly. For initiation, the client sends a CONNECT message to the broker and the broker responds with a CONNACK message and a status code. In this case, both client and broker need a TCP/IP stack. When the connection is established, then the broker keeps it open until the client sends a disconnect command or the connection break [27].

6 MQTT OVER LORAWAN

In this section, it is needed to specify how the key MQTT & CoAP messages can be sent over LoRaWAN class A MAC. It is needed to be mindful of the PHY layer limitations and MAC procedures and what are the fundamental performance limits associated with this. The MQTT has some limitations which are described below.

The function of MQTT: MQTT sends a command to output and receives a subscribe message. It is considered a publish and subscribe system where I can publish and receive messages as a client. It also maintains a simple communication between multiple devices. MQTT is low bandwidth and a simple messaging protocol which is designed for constrained devices. It allows me to send commands to control outputs, read and publish data from much more and sensor nodes. Consequently, it creates easiness to establish communication between multiple devices [28].

It operates over TCP: TCP has more processing and memory powered protocol than many of the lightweight, power constrained IoT devices. TCP needs more handshaking to set up communication relations before any messages can be replaced. This increases communication and times wake-up, which can affect long-standing battery consumption. However, connected devices of TCP tend to keep sockets open for each other with a persistent session. The power and memory requirements are also added here.

A centralized broker can limit scale: The scalability can be affected by a broker as there is extra overhead for each device connected to it [48].

6.1 Comparison of Protocols

MQTT protocol is the many to many protocols for passing messages. It stores data from numerous electronic devices and maintains remote device monitoring. It runs over TCP that means it supports event-driven message exchange through wireless networks.

Whereas the CoAP is a one-to-one protocol for transferring messages between server and client. This protocol is used to transmit a request to the application endpoints and send back the reply of services and resources in the application.

The AMQP protocol works at point-to-point for transporting message between two network processes. It also uses TCP/IP protocol to transfer message in between networks. AMQP contains three separate elements, namely Exchange, Message Queue and Binding. Typically, it tracks message while a message is sent from server to destination users. The comparisons of MQTT, CoAP and AMQP also described in Table 8 below [46].

Table 8. The analysis of messaging protocols for IoT Systems: MQTT, AMQP and CoAP

Specification	MQTT	AMQP	CoAP
Architecture	Client/Broker	Client/Broker or Client/Server	Client/Server or Client/Broker
Abstraction	Publish/Subscribe	Publish/Subscribe or Request/Response	Request/Response or Publish/Subscribe
Header Size	2 Byte	8 Byte	4 Byte
Message Size	Small and Undefined (up to 256 MB maximum size)	Negotiable and Undefined	Small and Undefined (normally small to fit in single IP Datagram)
Transport Protocol	TCP (MQTT-Sensor Network) can use UDP)	TCP, SCTP (Stream Control Transmission Protocol)	UDP, SCTP (Stream Control Transmission Protocol)

Moreover, machine-to-machine (M2M) communication protocol is used to manage remote application based on IoT devices. M2M protocol typically communicates between two machines which are predominantly cost-effective. It keeps the self-monitoring of machines and permits the systems to adjust according to the changing environment. Additionally, the Figure 20 conveys the relative difference of these messaging protocols which are based on their usage in accreditation and M2M/IoT from standard organisations.

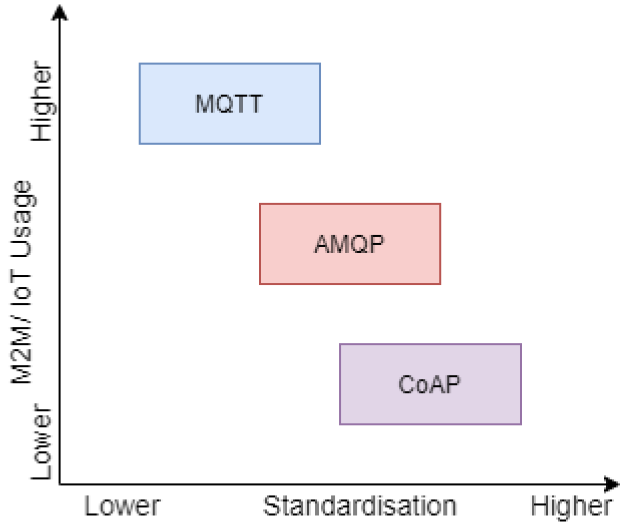


Figure 20. M2M/IoT usage vs standardisation [46].

The above graph shows that MQTT has been used by a large number of organisations. MQTT is described as a M2M protocol and has been supported and run by a large number of organisations such as Facebook, IBM, Cisco, Eurotech and Amazon Web Services (AWS) [46].

It is an efficient way to communicate from one system to many systems with some feedback from the recipient. So, the MQTT protocol has many-to-many communication protocol with ACK while the AMQP sends a point-to-point communication system with tracking. However, CoAP sends a response from receiver to sender. So, comparing AMQP over CoAP, AMQP tracks the massage until it reaches, so it is not efficient compared to CoAP.

The MQTT and CoAP both are useful as IoT protocols having some fundamental differences. The MQTT is a many-to-many communication protocol where the messages are passed between many clients through a central broker. However, CoAP primarily maintains a one-to-one protocol for transferring state information between server and client. MQTT communicates using publish or subscribe method while Request-Response method is used by CoAP. It commonly uses TCP protocol which is slower but reliable transfer typically used at Email and Web browsing. On the contrary, the CoAP mainly uses UDP protocol which is faster and nonguaranteed transfer. In this case, MQTT is connection-oriented and acknowledgement-based protocol whereas CoAP is connectionless without acknowledgement-based protocol. The MQTT uses asynchronous transmission while CoAP uses both synchronous transmission and asynchronous transmission. So MQTT protocol application reliability level is more than the CoAP protocol [46].

In this thesis work, an MQTT protocol is selected which is connection-oriented and ACK-based protocol. It is also quite a reliable protocol which makes sure data transfer from clients to the broker is based on acknowledgement. So, to transfer message from one broker to many clients; MQTT protocol is needed. That is why It is used for analysis as it works as a reliable ACK-based protocol which transfers message many-to-many.

6.2 MQTT over LoRaWAN

The goal of the analysis in this thesis is, how MQTT protocol runs over the LoRaWAN. MQTT is a message transmission protocol based on the lightweight, publish-subscribe network model. Here, it goes over the TCP/IP and provides lossless, ordered and bi-directional connections [29]. In this case, MQTT which message will be sent from ED to GW and finally MQTT server. The choices are some of the most popular protocols such as MQTT, HTTP, AMQP, and CoAP. All of them are suited for a specific scenario and environment. Well it has been selected the MQTT protocol because it serves the purpose better compared to others for this application. It delivers messages with a lower delay when the packet loss rate is low [30]. Figure 21 illustrates the MQTT connection over the LoRaWAN [29].

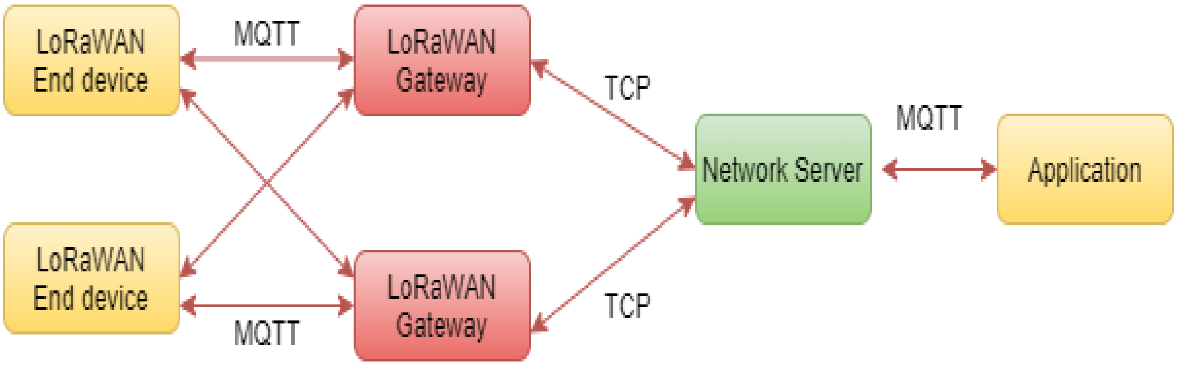


Figure 21. MQTT connection over the LoRaWAN [29].

The MQTT can use publish-subscribe message model to provide one-to-many message publish and decoupled applications. Three QoS levels are existing in MQTT as mentioned. “At most once”- the delivery message at most once situation, where messages can arrive corresponding to the best works of the underlying TCP/IP network. “At least once”- the delivery message in the at least once, a message is delivered at least one time to the receiver, but duplicates may occur. “Exactly once”- the delivery message occurs exactly once. Small data amounts are transmitted with a small header, a fixed length of only two bytes and protocol exchanges are minimized to decrease network traffic. The network connection runs over TCP/IP. MQTT protocol is thoroughly applied into the IoT solutions with very “Low-bandwidth and unreliable links” [29]. It has two transmission ways described below.

For Uplink: The sensor transmits MQTT data from LoRaWAN wireless to LoRaWAN GW. The GW will deal with these data and forward to a distant MQTT broker via the Internet.

For Downlink: A topic is subscribed by the ED in the MQTT broker, existing the update on the topic, the gateway will realize and transmit the MQTT data to Local LoRaWAN network [31]. The network structure for MQTT forwarding is depicted in Figure 22 below.

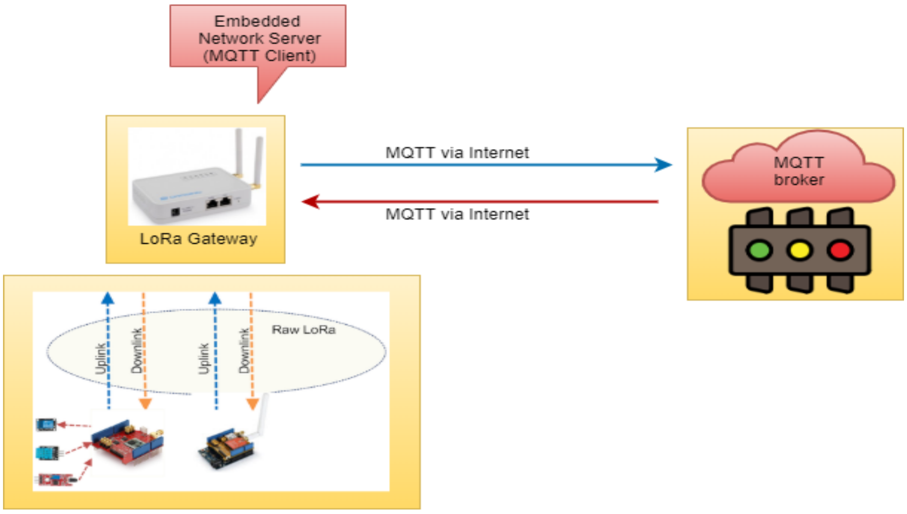


Figure 22. Topology for MQTT connection [31].

Sensor nodes are used in LoRaWAN, and they do not have to trouble with MQTT or with the MQTT Server. They just apply send/receive MQTT data to/from the LoRaWAN gateway. The LoRaWAN unpacks MQTT data to the gateway. The GW sends MQTT data through the TCP to NS. The MQTT broker is unable to communicate with the local LoRaWAN network [29].

6.2.1 MQTT procedures over LoRaWAN

The LoRaWAN device is one of the critical parts of this system. The LoRaWAN, a MAC -layer protocol that is implemented as a star-of-star topology to regulate LoRaWAN devices [35]. LoRaWAN device collects the data of activity and location information, then sends them to the LoRa GW. In this system, the device works in Class A mode, which is the lowest power consumption mode in LoRa systems [36]. Later the application server (AS) transmits the message to MQTT broker. In this case, MQTT protocols higher in the protocol stack can also be applied for the communication among GW, NS, and the AS. Figure 23 illustrates MQTT over LoRaWAN.

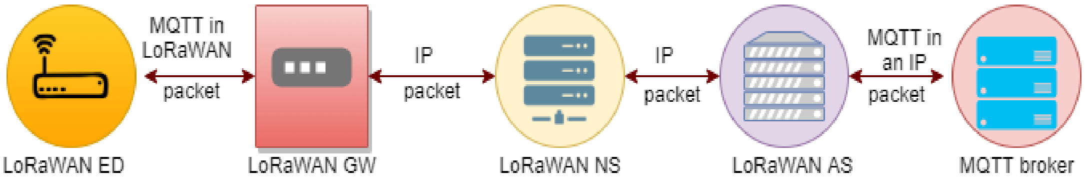


Figure 23. MQTT message over the LoRaWAN [36].

According to Figure 24, a sequence diagram is drawn to show how messages are transferred from the ED to the MQTT server. In this section, it has chosen an elaborate lightweight publish-subscribe IP protocol (i.e. a LoRaWAN payload can be sent to many MQTT clients simultaneously each serving a different purpose or application) [36]. Likewise, secure one-to-many communication, UDP is more vulnerable to spoofing and denial of service attacks. In this thesis work, I have selected the MQTT protocol for this sequence diagram. The LoRaWAN solution sequence is explained below in Figure 24.

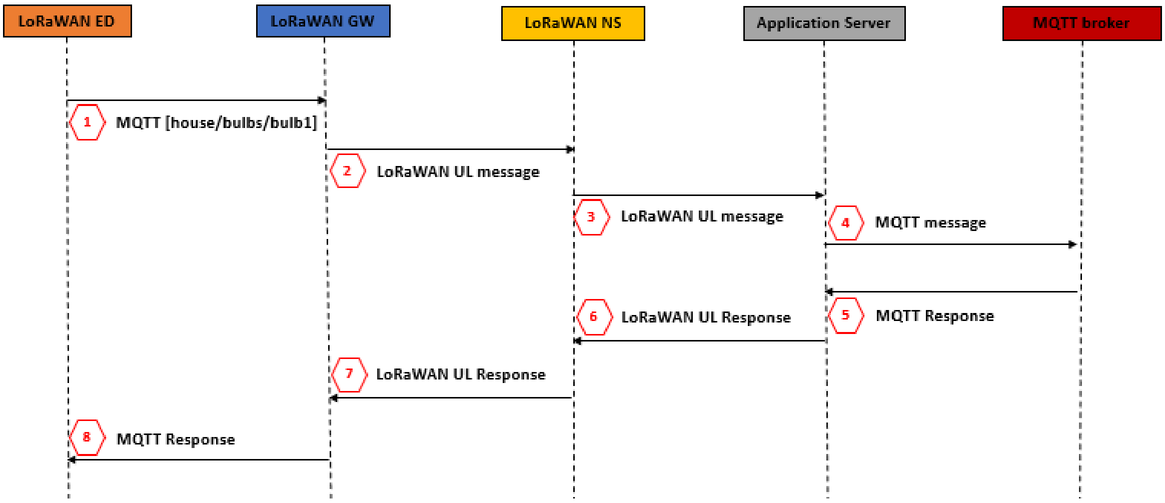


Figure 24. LoRaWAN solution sequence diagram.

To give an example, an ED is expected to send sensor data (temperature and humidity), (1 in hexagon shape as mention in state diagram) through LoRaWAN network to an application server so that a user can monitor an application (4 in hexagon shape as mention in state diagram).

- An experiment assuming a use case scenario where a user wants to turn ON / OFF a bulb resided at ED (1) from a remote position with an application (4). "ON" and "OFF" are the bulb state as payload where the payload size is 2 bytes (for two characters in “ON”) or 3 bytes (for three characters in “OFF”), respectively. Experiment setup also includes connect, publish; and disconnect which is discussed in detail in 6.3.2 – 6.3.4.
- Assuming ED has three bulbs: bulb1, bulb2 and bulb3. "ON" or "OFF" is their payload where payload size is two or three respectively. All these have same request pattern, but here bulb1 request pattern is shown in above Figure 24.
- LoRaWAN GW sends the message (received from end device) to the LoRaWAN network server (marked 2 as shown in the above figure).
- The network server reverses the prior process (i.e convert hex to ASCII of the message) and sends the newly available data to the application server (marked as 3 on the figure).

- Finally, MQTT server (broker) sends the received message "bulb1, bulb2 and bulb3" to the application (marked as 4 on the figure).

Here, steps 5 – 8 are illustrated the response happening whereas steps 1 – 4 are requested in the model. In the response, encoding and decoding takes place into step 6 and 8, respectively while these takes place into step 1 and 3 in the request cycle. The simulation is done in MQTT [40].

6.3 Analysis of performance of MQTT over LoRaWAN

The data transmission protocol analysed in this thesis provides an MQTT over LoRaWAN operated. The MQTT client publishes a message on a specific topic. The message is delivered by the MQTT broker to all the clients subscribed to that topic and sends the command via LoRa to the end node. The LoRaWAN, a MAC layer protocol that is implemented as a star-of-star topology to regulate LoRa devices. Class A in MAC layer is selected for analysis performance where ED sends an MQTT message to the gateway. Finally, for the EDs of Class A, each uplink transmission is followed by the two receive windows (RX1 and RX2) as this is illustrated in Figure 25.

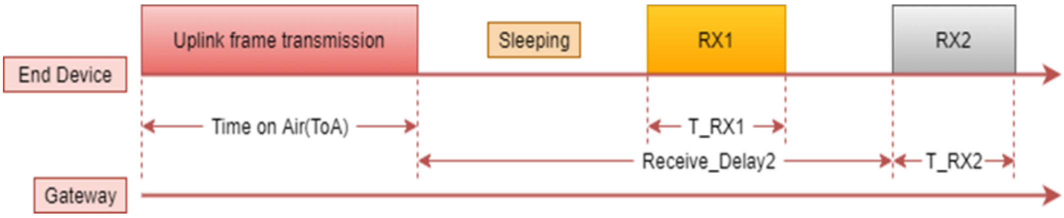


Figure 25. LoRaWAN class A ED uplink transmission phases [42].

According to the above Figure and following the common practice [41], the RECEIVE_DELAY 1 is 1s for RX1 window and RECEIVE_DELAY 1 is 2s. 1s and 2s are default value both of the windows (RX1 and RX2) [42].). Here RX1DROffset default value is zero; that is why there is nothing to make delay. Where RX2 uses a fixed data rate and frequency [41].

6.3.1 LoRaWAN transmission for MQTT

In terms of LoRa, the amount of spreading code applied to the original data signal is referred as the spreading factor (SF). There are six spreading factors (SF7 to SF12) in LoRa modulation. The LoRaWAN uses spread factors from 7 to 12. The SF7 is the shortest time on-air, and the SF12 will be the longest. Here SF = 6 is a different use case for the highest data rate transmission possible with the LoRa modem. When it is used the lower range of SF values, then the data rate is very high, and air-time is short. So, SF is the key variable of the quality of the service. Higher SFs means longer range but limits the QoS. The DR in achievable communication can be calculated from the bandwidth BW (Hz), coding rate (CR), and the SF. Two bandwidths are used (125kHz and 250kHz) in LoRa [41]. According to different locations LoRa uses different bands. Depending on TCP, MQTT uses TLS (Transport Layer Security) for data encryption and secure communication [36]. All the data are extracted through the application service by deploying a simple application interface (API). In this case, the MQTT broker is used to obtain the above information. In the MQTT procedure over the LoRaWAN, "Things network" is used [35]. The SF and the data transmission rate relationship is defined as follows. The knowledge of the key parameters that can be operated by the user, it is described the LoRa symbol rate as:

$$RS = {}^{BW}\!/_{2^{SF}}, \tag{2}$$

with the definition of equation (2), it is shown the data transmission rate and relationship among Bandwidth (BW), SF and Symbol Rate (RS) where SF means spreading factor and BW is the programmed bandwidth. The transmitted signal referred to a constant packet signal. Consistently, one chip is sent per second per Hz of bandwidth [37]. The frame format of LoRa can be either explicit or implicit where a short header is included in explicit packet containing information regarding the bytes, coding rate and CRC used in the frame. The packet format is displayed in the following Figure 26. LoRa packet comprises three elements such as preamble, header and payload. I calculated the on-air-time where $n_{preamble}$ = 8, explicit header = enabled, CRC = enabled, payload length, CRC = 1 and BW = 125 kHz.

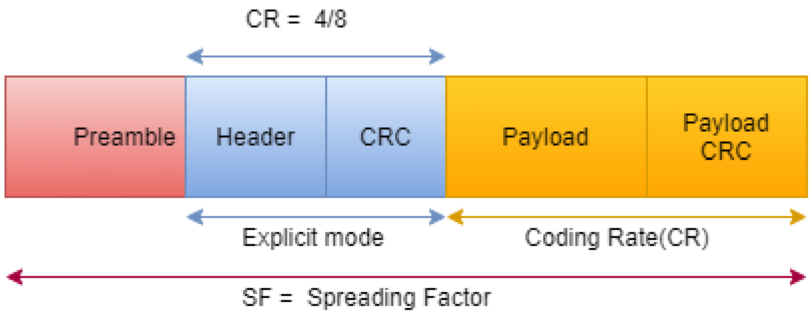


Figure 26. LoRa frame structure [46].

However, the on-air-time (ToA) of the frame is an important matter for real-time applications. With the BW, SF and code rate (equals 4/5) time required to transmit a LoRa frame can be calculated. The packet duration of LoRA is the summation of the duration of the preamble and the payload packet [46].

$$T_oA = T_{packet} = T_{frame} = T_{preamble} + T_{payload}. \tag{3}$$

$T_{preamble}$ is varied on the $T_{sym,}$ which is presented by equation (5) and programmable length of the modem records $n_{preamble}$ in equation (6). The LoRaWAN 1.0 denotes default $n_{preamble}$ as 8. T_{sym} means symbol duration. It is increases when LoRa bandwidth decreases

$$T_{sym} = {}^{1}\!/_{RS}. \tag{4}$$

$$T_{preamble} = (n_{preamble} + 4.25)T_{sym}, \tag{5}$$

from the equation (5), $n_{preamble}$ is defined as the programmed preamble length which is taken from the registers RegPreambleLsb and RegPreambleMsb. The next formula provides the number of the payload symbols [37].

$$\left[\begin{matrix} n_{payload} = 8 + \max(ceil(\left[\frac{8PL-4SF+28+16CRC-20IH}{4(SF-2DE)}\right](CR+4), 0) \\ T_{payload} = n_{payload} \times T_{sym} \end{matrix}\right], \qquad (6)$$

In the above equation, the LoRaWAN specification specifies CRC=1 and IH=0 for uplink, and CRC=0 and IH=0 for downlink. From the above Equations, PL means the number of bytes of payload. For LoRaWAN default, IH = 0 when explicit header mode is enabled and IH = 1 when implicit header mode is used. DE = 1 shows use of low data rate optimization and 0 = disabled. Where CRC indicates the presence of the payload CRC = 1, means on and CRC = 0, means off. The programmed coding rate ranges from 1 to 4 [46]. For LoRaWAN default =1 [37]. Whereas according to the EU868, the limitations of data rates and the payload is shown as a Table 9 in below.

Table 9. Limitation of data rates and MAC [41] for EU 868 MHz band

Data rate	Spreading Factor	The maximum LoRaWAN MAC payload, bytes
0	12	59
1	11	59
2	10	59
3	9	123
4	8	230
5	7	230
6	7	230

In addition, MQTT protocol is used as a transport vehicle or interoperability middleware on a full TCP/IPv4-stack or UDP layer to connect end devices and transmit data over the LoRaWAN. According to the header size, the IP header size is 20 bytes and the TCP header size is 20 bytes [11]. However, the maximum size limit is 65,535 bytes in TCP. The TCP datagram is shown in Figure 27.

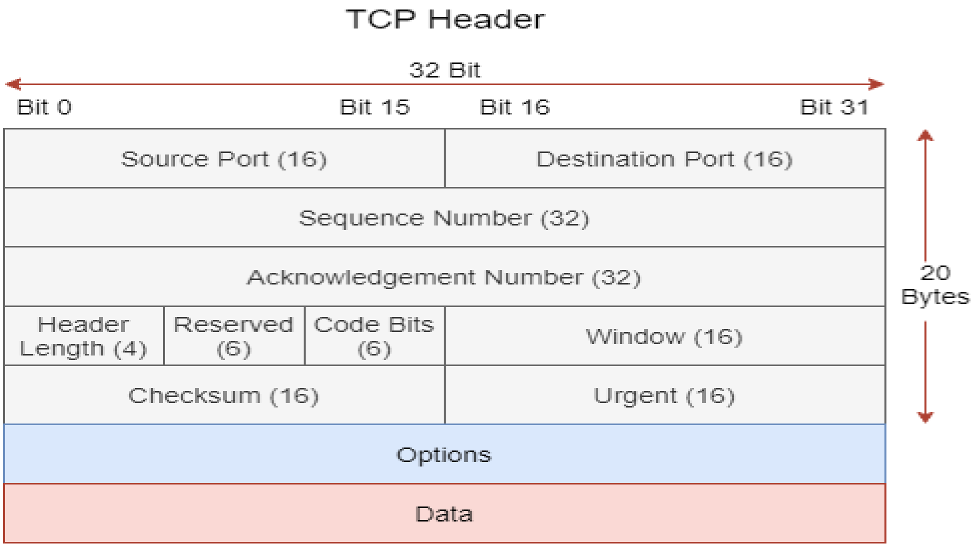


Figure 27. TCP overhead.

The header of TCP is 20 bytes long and the format and header of TCP is described in detail below:

- Source port – this field is a16-bit. The application port number of the host is specified for sending the data.
- Destination port - It is included a 16-bit field. In the destination port, this field is given the port number of the application requested.
- Sequence number - This field (32 bits) is used to re-transmit missing or destruction data segments and used to put the data back in the correct order.
- Acknowledgement number - It is also a 32-bit field which is employed by the receiving host to acknowledge the successful transfer of segments based on which the source forwards the following stream of data segments.
- Header Length - This field (4 bits) identifies the number of 32-bit words in the header. It also implies the length of the TCP header to know where the actual data starts.
- Reserved - This is a 3 bits field as well as value always set to 0.
- Code Bits (Flags) - It is a 9 bits field with each have a particular purpose [11].

6.3.2 CONNECT

The connection of MQTT always exists between client and broker. So before sending or receiving data using MQTT, a client needs to establish the connection to the broker. For initiation, the client sends a CONNECT message to the broker and the broker responds with a CONNACK message and a status code. In this case both client and the broker need to have a TCP/IP stack. After establishing the connection, the broker keeps it open until the client sends a disconnect command or the connection breaks. MQTT is located behind the router and it uses network address translator (NAT) in order to translate IP address from private network IP to public one. If either client sends a disconnect command or it loses the link, the connection will drop. When the connection has been established, it transmits and receives messages [27]. After the initiation of a connection, the client sends a command message to the broker. For connect MQTT message, uplink and downlink on air time calculation are calculated according to the equation (3), with the help of air time calculator [39]. Where, DE is set 1 which means the use of the low data rate optimization, and DE = 0 when disabled. So low data rate optimizes (enable DE = 1, disable DE = 0). This low data rate is enabled for spreading factor >= 11 and bandwidth 125kHz. Here CR is called the programmed coding rate, ranging from 1 to 4, and is set to 1 following the calculation. T_{sym} is in the symbol duration [46]. The DR, SF and LoRaWAN MAC are run through the EU 868 band standard [41]. In EU 868 standard, LoRaWAN MAC values are found. Here the bandwidth 125 kHz is used for DR0 to DR5 and DR6 is used for 250 kHz [41]. So, the transmission time needed for MQTT CONNECT over the LoRaWAN for different SFs is given in Table 10.

Table 10. The total time needed for MQTT CONNECT over LoRaWAN for different SFs

Data rate (DR)	Spreading factors (SF)	Maximum uplink payload, bytes		Uplink on-air time, s	Downlink payload, bytes		Downlink on-air time, s	Total duration, s	
		LoRaWAN MAC	MQTT message		LoRaWAN MAC	MQTT message		Response in RX1	Response in RX2
0	12	59	6	2.580	57	4	2.449	6.029	7.029
1	11	59	6	1.406	57	4	1.333	3.739	5.855
2	10	59	6	0.653	57	4	0.620	2.273	4.804
3	9	123	70	0.647	57	4	0.337	1.984	4.798
4	8	250	197	0.660	57	4	0.186	1.846	4.811
5	7	250	197	0.376	57	4	0.104	1.480	4.527
6	7	250	197	0.194	57	4	0.052	1.246	4.345

Equations used:

$$MQTT\ Message\ (MM) = \text{Message Payload (MPL)} + \text{MQTT Header (MH)}, \quad (7)$$

$$\text{LoRaWAN MAC (Uplink)} = \text{MQTT Message (MM)} + \text{TCP Header (TCPH)} + \text{IP Header (IPH)} + \text{LoRaWAN (LH)}, \quad (8)$$

$$\text{LoRaWAN MAC (Downlink)} = \text{MQTT Header (MH)} + \text{TCP Header (TCPH)} + \text{IP Header(IPH)} + \text{LoRaWAN(LH)}, \quad (9)$$

The equations (7)-(9) are used to calculate the LoRaWAN MAC uplink and downlink for CONNECT to further use in equations (10)-(11) to find the corresponding response (RX1 or RX2). Details of the notations and respective values are shown following:

For Example, DR0 (CONNECT):

- MQTT Payload (MPL) = 4 bytes
- MQTT Header (MH) = 2 bytes
- MQTT Header (MH) for CONNACT = 4 bytes
- IP Header (IPH) = 20 bytes
- TCP Header (TCPH) =20 bytes
- LoRaWAN (LH) = 13(Header) bytes
- MQTT Message (MM) = MPL + MH = 4+2= 6 bytes
- LoRaWAN MAC (Uplink): MM+TCPH+IPH+LH = 6+20+20+13 = 59 bytes
- LoRaWAN MAC (Downlink): MH+TCPH+IPH+LH = 4+20+20+13 = 57 bytes

Following equations-(10) and (11) are used to calculate RX1 and RX2:

$$\text{Response in RX1 (1st receive window)} = \text{DR (uplink on} - \text{air time)} + 1\ \text{(RECEIVE Delay 1)} + \text{DR (downlink on} - \text{air time)}. \quad (10)$$

$$\text{Response in RX2 (2nd receive window)} = \text{DR (uplink on} - \text{air time)} + \\ \text{2 (RECEIVE Delay 2)} + \text{DR0 (downlink on} - \text{air time).} \quad (11)$$

RX2 uses a fixed data rate and frequency. The default parameters of RX2 are 869.525 MHz / DR0 (SF12, 125 kHz). Here RX1DROffset default value is zero; that is why there is nothing to make delay [41].

For MQTT CONNECT, the header size is always present, which is 2 bytes [26]. Where the TCP header overhead is 20 bytes [11] . However, in downlink CONNACK packet is 4 bytes where there is no variable header and payload [26]. Furthermore, the LoRaWAN header size between 13 to 28 bytes can be taken [32]. In this work, 13 bytes are considered for MQTT CONNECT as LoRaWAN header size. The uplink and downlink transmission time are varied for CRC and IH. In uplink transmission, CRC is one and downlink transmission CRC and IH are zero [46]. In both cases, time is reduced gradually. Here the spreading factors are proportional to the transmission time and data rates are inversely proportional to the transmission time.

6.3.3 PUBLISH

When an MQTT client is connected to the broker, then it can publish messages. An MQTT client can publish messages very soon when it connects to a broker [27]. The small size of the protocol headers and the byte array message payload keep messages short. According to the MQTT publish message, the maximum number of bytes which is put into PUBLISH packet sent over the LoRaWAN SF is provided as a table. The calculation method is similar in Table 10, according to the equation (3). Table 11 shows the maximum number of bytes it can put into PUBLISH packet sent over the LoRaWAN SF.

Table 11. The total time needed for MQTT PUBLISH over LoRaWAN for different SFs

Data rate (DR)	Spreading factors (SF)	Maximum uplink payload, bytes		Uplink on-air time, s	Downlink payload, bytes		Downlink on-air time, s	Total duration, s	
		LoRaWAN MAC	MQTT message		LoRaWAN MAC	MQTT message		Response in RX1	Response in RX2
0	12	74	21	3.072	62	9	2.613	6.685	7.685
1	11	74	21	1.678	62	9	1.424	4.102	6.291
2	10	74	21	0.776	62	9	0.661	2.437	5.064
3	9	110	57	0.588	62	9	0.360	1.948	4.876
4	8	230	177	0.634	62	9	0.198	1.832	4.922
5	7	230	177	0.360	62	9	0.111	1.471	4.648
6	7	230	177	0.180	62	9	0.055	1.235	4.468

$$\text{MQTT Message (MM)} = \text{Message Payload (MPL)} + \text{MQTT Header (MH)}, \tag{12}$$

$$\text{LoRaWAN MAC (Uplink)} = \text{MQTT Message (MM)} + \text{TCP Header (TCPH)} + \text{IP Header (IPH)} + \text{LoRaWAN (LH)}, \tag{13}$$

$$\text{LoRaWAN MAC (Downlink)} = \text{MQTT Header (MH)} + \text{TCP Header (TCPH)} + \text{IP Header (IPH)} + \text{LoRaWAN (LH)}, \tag{1}$$

The equations (12)-(14) are used to calculate the LoRaWAN MAC uplink and downlink for PUBLISH to further use in equations (10)-(11) to find the corresponding response (RX1 or RX2). Details of the notations and respective values are shown below:

For Example, DR0 (PUBLISH):

- MQTT Payload (ML) 12 bytes (Hello world!) [49].
- MQTT Header (MH) = 9 bytes
- IP Header (IPH) = 20 bytes
- TCP Header (TCPH) = 20 bytes
- LoRaWAN Header (LH) = 13 bytes
- MQTT Message (MM): MH+ML= 12+9 = 21 bytes
- LoRaWAN MAC (Uplink): MM+TCPH+IPH+LH= 21+20+20+13 = 74 bytes
- LoRaWAN MAC (Downlink):MH+TCH+IPH+LH = 9+20+20+13 = 62 bytes

Similarly, RX1 and RX2 are calculated from equations-(10) and (11) as like previous calculations for CONNECT. Moreover, RX2 uses a fixed data rate and frequency as previous. The default parameters of RX2 are 869.525 MHz / DR0 (SF12, 125 kHz). Here RX1DROffset default value is zero; that is why there is nothing to make delay [41].

For MQTT publish, the header is 9 bytes where the payload is optional, and variable-length is none [49].This above Table is also correlated with Table 10 because of the data rate and payload size. When the payload is higher, it gets a shorter time duration for publishing messages. Payload size increases according to the increasing data rate while total time duration decrease. Lower data rate means higher time duration but smaller payload size. Comparing with Tables, it is got higher time to publish messages because of its payload is different sizes.

6.3.4 DISCONNECT

In MQTT, applying the Last Will and Testament (LWT) feature, it notifies other clients about an ungracefully disconnected client. If it connects to a broker, each client can specify its last will message. The last will message a standard MQTT message with a topic, QoS, payload and retained message flag. In this case, the broker can store the message until it detects that the client has disconnected ungracefully. Answering the ungraceful disconnect, the broker will send the last-will message to all subscribed clients of the last-will message topic. But if the client disconnects graciously with a correct DISCONNECT message; the broker will dispose of the stored LWT message [45]. Here in MQTT DISCONNECT, there is no variable payload. The calculation method is similar to the previous Table 10 for uplink according to the equation (3). However, there is no payload and variable header in disconnect packet. So, the disconnect packet is fixed 2 bytes [26]. Whereas, data rates, spreading factors and LoRaWAN MAC are selected for EU 868 band standard [41]. Consequently, the transmission time needed for MQTT DISCONNECT over LoRaWAN for different SFs is given in Table 12.

Table 12. The total time needed for MQTT DISCONNECT over LoRaWAN for different SFs

Data rate (DR)	Spreading factors (SF)	Uplink payload, bytes		Uplink on-air time, s
		LoRaWAN MAC	MQTT message	
0	12	59	2	2.58
1	11	59	2	1.41
2	10	59	2	0.65
3	9	59	2	0.36
4	8	59	2	0.19
5	7	59	2	0.11
6	7	59	2	0.055

$$\text{MQTT Message (MM)} = \text{Message Payload (MPL)} + \text{MQTT Header (MH)}, \quad (15)$$

$$\text{LoRaWAN MAC (Uplink)} = \text{MQTT Message (MM)} + \text{TCP Header (TCPH)} + \text{IP Header (IPH)} + \text{LoRaWAN (LH)}, \quad (16)$$

Equations (15)-(16) are used to calculate the LoRaWAN MAC uplink for DISCONNECT. Details of the notations and respective values are shown in following:

For Example (DISCONNECT):

- MQTT Header (MH) = 2 bytes
- IP Header (IPH) = 20 bytes
- TCP Header (TCPH) = 20 bytes
- LoRaWAN Header (LH) = 17 bytes
- MQTT Message (MM) = 2 bytes
- LoRaWAN MAC (uplink): MM+TCPH+IPH+LH = 2+20+20+17= 59 bytes

In the above table, the different transmission time can be found out. The transmission time gradually decreases in respect to spreading factors. So, by analysing the spreading factors (SF7 to SF12) in LoRa modulation, longer time duration and smaller spreading factors are found. In this case, two types of bandwidth are used for air-time calculation. The DR06 used is 250 kHz bandwidth and remaining DRs used are 125 kHz [41].

7 DISCUSSION

The IoT network contains numerous resources such as actuators, sensors and some constrained devices. There are several types of protocol in IoT networks. In this thesis, MQTT and COAP protocol are selected over the LoRaWAN network. The key challenges include energy consumption, resource, low latency, low-cost, high bandwidth, security, privacy, interoperability, scalability, reliability and availability. Respectively in the technology field, there are several long-range technologies such as LoRaWAN, NB-IoT, and LTE-M. All of them are suited for a specific scenario and environment. In this thesis work, LoRaWAN is theoretically analysed to transfer small data packet in the long distance. The main task is to analyse the performance of the MQTT protocol over LoRaWAN where MQTT delivers messages with a lower delay when the packet loss rate is low. In the theoretical assumption part, the CONNECT, DISCONNECT and PUBLISH messages of MQTT are used. With the analytical approach, MQTT protocols are used as transport data on a full TCP/IP-stack to connect end devices and transmit data over the LoRaWAN. In this thesis, MAC layer options are described, specifically LoRa MAC Class A uplink and downlink.

The obtaining results from the theoretical analysis are shown in this work which demonstrates the communication method over the LoRaWAN with ED, GW, AS and MQTT server. Furthermore, three messages of MQTT such as CONNECT, DISCONNECT and PUBLISH time duration have been numerically demonstrated for different SFs. The RX1 and RX2 ACK time is found minimum 1s and 2s, which is shown in the analytical section 6.3.2 and 6.3.3. Performance comparison of LoRaWAN for MQTT lightweight message is also shown in the analytical section as a Table.

Moreover, uplink time and downlink time are found different from results. After analysing the spreading factors (SF7 to SF12) in LoRa modulation, longer time duration and smaller payload is found for longer spreading factors. In comparison, shorter duration and bigger payload is found for smaller SFs. Therefore, in the LoRa modulation, I can summarize that spreading factors are proportional to the time duration. Consequently, DR and payload are inversely proportional to the time duration of the protocol messages.

8 CONCLUSIONS

The Internet of Things (IoT) is dignified to reshape how people, industries and enterprises communicate with customers and users. IoT ecosystem is generating tremendous business opportunities, eventually opening the doors for innovation. Network protocols, technologies and standards such as Narrowband IoT (NB-IoT), LoRaWAN, Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP) are being developed to support a wide range of IoT applications and services.

This thesis represents the analytical performance study of the effect of different SF or DR alongside different payload sizes (the message length) over LoRaWAN by using MQTT and CoAP protocols. Three types of messages (connect, disconnect, and publish) are used to analysis the connecting time and disconnecting time over the LoRaWAN.

This theoretically based analysis supports that the duration of connecting and disconnecting time depends on the SF and payload size. The MQTT and CoAP protocols are more suitable because of their features (such as power consumption, header size etc.). The LoRaWAN ensures pervasive connectivity in both outdoor & indoor applications while maintaining simple network configuration and management. MQTT is suitable for low-bandwidth, constrained devices and high-potential or untrustworthy networks. It can contain a huge number of clients (up to 10k devices) and a server known as "broker".

The results obtained from speculation are presented in this work which demonstrates the communication method among LoRaWAN with ED, GW, AS and MQTT server. Moreover, CONNECT, DISCONNECT and PUBLISH time duration used by MQTT messages have been evaluated for different SFs. The RX1 and RX2 acknowledgement, the minimum time needed to establish an MQTT connection is one second, while the maximum is two seconds. which are shown in the analytical part as a Table 10. Furthermore, uplink time and downlink time are found different from result parts. After analysing the spreading factors (SF7 to SF12) in LoRa modulation, shorter time duration and bigger payload is found for shorter spreading factors. On the contrary, longer duration and smaller payload is found for longer SFs. Hence, spreading factors in LoRa modulation are proportional to the time duration. Consequently, DR and payload are inversely proportional to the time duration of the protocol messages. This study is expected to represent the fundamentals and future trends related to the MQTT protocol.

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